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An evaluation of the EM instruments' Loss-of-Metallic-Area (LMA) signals

L.B. Geller and G. Rousseau

MRL 91-100 (TR)

June, 1992

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MICROMEDIA

AN EVALUATION OF THE EM INSTRUMENTS' LOSS-OF-METALLIC-AREA (LMA) SIGNALS

by

L.B. Geller* and G. Rousseau**

ABSTRACT

At the request of both the mining industry and the mine regulatory authorities, CANMET undertook a major research project in 1986 to investigate the reasons for continued mine-shaft wire-rope failures, or near failures, occurring in spite of rope testing with EM instruments on a mandatory basis at regular intervals. The work was supported by industry and the authorities, on both a national and international level.

This report describes test-results obtained through joint Canadian/US efforts, within the overall framework of the aforementioned project. In particular the authors discuss, and analyse, the laboratory test-results obtained with the loss-of-metallic-area (LMA) detector signals of a Canadian and an American EM tester, using two mock-up assemblies, and different size wire-ropes and steel rods. The testers are representative of the two basic North American, commercially available, sensor-head constructions with strong permanent magnets. The authors' objective was to examine the instruments' LMA detector signals with special reference to operational requirements.

This report is a companion of CANMET division report MTL #91-33, in which the same two testers' local-fault (LF) detector signals were described and analyzed.

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Keywords: Wire-ropes; Non-destructive-testing; Electro-magnetic instruments; LMA-signal; Evaluation

ÉVALUATION DES SIGNAUX DE PERTE DE SURFACE MÉTALLIQUE (PSM) DES INSTRUMENTS ÉM

par

L.B. Geller* et G. Rousseau**

RÉSUMÉ

À la demande de l'industrie minière et des organismes de réglementation des mines, CANMET a entrepris en 1986 un grand projet de recherche pour étudier pourquoi il continue de se produire des ruptures ou quasi-rupture des câbles de puits de mine même si ces câbles ont été obligatoirement et régulièrement vérifiés au moyen d'instruments ÉM. L'industrie et les organismes ont collaboré à ce travail à l'échelle tant nationale qu'internationale.

Le présent rapport décrit les résultats d'essais obtenue grâce aux efforts conjoints du Canada et des États-Unis, ainsi que le cadre général du projet susmentionné. Les auteurs présentent et analysent notamment les résultats d'essais de laboratoire obtenus avec les signaux de deux contrôleurs ÉM de détecteur de perte de surface métallique (PSM), un canadien et un américain, en utilisant des montagnes de simulation, et des câbles et des tiges d'acier de différentes tailles. Les contrôleurs sont représentatifs de deux modèles nord-américains à capteurs munis d'aimants permanents puissants, qui sont disponibles dans le commerce.

Le présent rapport complète le rapport de division LTM # 91-33 de CANMET, dans lequel les signaux de détection des défauts locaux (DL) des deux contrôleurs dont décrits et analysés.

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Mots clés: câbles métalliques; essai non destructif; instruments électromagnétiques; signal de PSM; évaluation.

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INTRODUCTION

The results described, and analyzed, in this report were obtained by joint Canadian/US work within the framework of a CANMET project, begun in 1986. The overall objective was to examine the reasons for continued mine-shaft rope failures, or near failures, despite mandatory wire-rope examinations with — to use the regulatory terms — 'approved' electro-magnetic (EM) instruments and 'competent' operators at regular intervals. The project contained both in-house and contracted work phases. Results were described in a series of CANMET reports (1 through 25). One of these (6) is a companion report of the present one, insofar as: (a) in both cases the same EM testers were used, namely the Canadian Magnograph, and the American LMA-250 series instruments. It should be noted that the *modus operandi* of these testers is representative of the two basic flux detection methods currently used in North America by commercially available EM instruments, namely by the ones with Hall-sensors (or equivalent), and by the ones with inductive-coils, (b) in reference 6 test results were described, and analyzed, that were obtained with the local-fault (LF) detector channels of these EM instruments; in the present report we do the same with the signals of the loss-of-metallic-area (LMA) detector channels, and (c) the instrument operators were the same in both cases.

Our tests were designed with 'real-life' requirements in mind. Basically, the question to be answered was: how accurately do the LMA signals of these instruments represent operational realities. We wish to emphasize, though, that merely the principles incorporated in our test-procedures apply to any and all instruments represented by the design features of the specific Magnograph and LMA-250 testers used. Quantitatively, however, individual results obtained by others with the same type of instruments will, very likely, differ from ours. In this context we refer to the currently reported, and widely differing results, that were obtained with the same LMA-250 sensor-head, but different consoles. The considerable differences between results reported by Magnograph operators 'A' and 'B' should also be noted; this situation is indicative of how carefully proper calibration procedures must always be adhered to, if spurious results are to be avoided. Moreover, it should be mentioned that the Magnograph involved in our test-series was not in pristine condition: it had been used before in the field for many years by others, under circumstances unknown to us, and outside of our control.

TEST PARAMETERS

In the series of photographs reproduced in Figures 1 through 5 (Appendix 1) we illustrate the instruments, mock-ups, and general test set-ups used to generate LMA signals of current interest. Specifically, the use of a 3-ft long 'large', and a 3-ft long 'small' mock-up assembly will be noted. These were specially designed by G. Rousseau so that the sensor-head could be loaded with steel-rods in a variety of orderly and preplanned ways; without their use this process is difficult to achieve, due to the instruments' powerful permanent magnets. Each mock-up contained six peripheral and one central non-magnetizable stainless-steel tubes, with inside diameters (I.D.) of 5/8 in. and 3/8 in., for the 'large' and 'small' mock-ups, respectively. Seven 3/32 in. steel rods were used to completely fill each 3/8 in. tube, and either eleven 1/8 in., or seven 5/32 in. rods to do the same with the 5/8 in. tubes. The outside diameter (O.D.) of the mock-ups' envelope-circle (see Fig. 4 of ref. 6) was $1\frac{7}{8}$ in., and $1\frac{1}{4}$ in., respectively. The O.D. of the five non-magnetizable 'Delrin' structural discs (two at each end, one in the centre, and one each at 6-in. from the centre, as can be seen clearly in Figures 2a, 3b, and 5a) was chosen to fit inside the EM instruments' sensor-heads. They were of $2\frac{1}{4}$ in. diameter, and $1\frac{5}{8}$ in. diameter, for the 'large' and the 'small' mock-ups, respectively.

Use of the mock-up assemblies was a *sine qua non* requirement when testing the instruments' responses to such operational problems as different location of the rope-anomalies (e.g., in the rope-core), and/or their different distribution. An extensive series of tests was, however, also devised, which did not involve the use of mock-ups. In this case operational wire-ropes in the sensor-heads were either represented by a bundle of 3-ft long steel-rods (as detailed in Appendix 2), or by 8-ft lengths of actual wire-rope samples (seen on the floor in Fig. 5a). The latter included the following constructions and metallic cross-sectional areas (with their corresponding *mass per unit length* values listed in brackets): (1) 1/2 in. diameter, 6×26, IWRC, of 0.1162 in^2 (0.655 kg/m); (2) $1\frac{1}{8}$ in. diameter, 6×25, IWRC, of 0.6265 in^2 (3.512 kg/m); (3) $1\frac{1}{2}$ in. diameter, 6×25, IWRC, of 1.0881 in^2 (6.101 kg/m); (4) $1\frac{3}{4}$ in. diameter, 6×25, IWRC, of 1.4825 in^2 (8.320 kg/m); (5) 2.0 in. diameter, 6×25, IWRC, of 1.9409 in^2 (10.88 kg/m), and; (6) $1\frac{7}{16}$ in. diameter, FLC, hoist-rope of 1.2887 in^2 (7.113 kg/m). For the 3-ft long steel rods, available for filling the mock-ups, we used the following data: (1) nominal 3/32 in. diameter, of 0.00690 in^2 (0.0347 kg/m), (2) nominal 1/8 in. (0.126 in.) diameter, of 0.0124 in^2 (0.0627 kg/m), and (3) nominal 5/32 in. diameter, of 0.0191 in^2 (0.0962 kg/m).

TEST DETAILS

The extensive series of tests, described in this report, included use of: the Magnograph and LMA-250 instruments, in either case with alternate consoles and with several operators; tests with and without mock-ups; as well as tests with both arbitrary LMA Gain Potentiometer dial-settings and with calibrated settings (as a function of the amount of metal inside the sensor-head at the point of instrument calibration). As may be seen, these tests were designed to involve both hardware and operator related problems insofar as: (1) the EM instruments represented both of the basic designs currently in use in North America, and (2) a number of operators were involved, and these were unaware of each other's results.

Full details of these tests are listed in Appendix 2.

ANALYSIS OF TEST RESULTS

All tests were designed to examine the EM instruments' response to specific circumstances of practical import. In particular, the aim was to examine design related characteristics, such as: (A) incomplete magnetic saturation, (B) practical consequences of incomplete magnetic saturation, (C) saturation of the electronic circuitry — integrators, (D) saturation of the electronic circuitry — output amplifiers, (E) accuracy of calibrated LMA Gain Potentiometer settings, and corollary matters, and (F) 'repeatability' aspects of the test-results, and corollary matters.

(A) Incomplete magnetic saturation

With inductive-coil type instruments, such as the LMA-250

As mentioned elsewhere (e.g., in ref. 17, p.3), all EM instrument designers are faced with the problem of incomplete magnetic saturation of a rope's metallic cross-sectional area, above a certain *'mass per unit rope-length'* value. The reason is that, if complete magnetic saturation is to be achieved with increasing rope-sizes, the size of the permanent magnets in the instruments' sensor-heads must also be increased as a function of the ropes' increasing metallic cross-section: this, obviously, is a *non sequitur* proposition, beyond a practical limiting sensor-head weight. Consequently, the relationship between a rope's total metallic cross-sectional area (MA), as expressed in kg/m, and the cumulatively measured induced voltage is only linear — as the amount of metallic mass in the sensor-head decreases/increases — up to a certain limiting value. This value was seen to be some 3-4 kg/m for the LMA-250 (Fig. 6). This value might need reexamination by means of more accurate measurements.

We obtained this correlation by combining the results of the 10 separate steps performed in test #10c, at a constant LMA Gain Potentiometer dial-setting of 1. Such a subdivision of the test was necessary due to a physical design characteristic of the EM instruments with inductive-coils. This characteristic is known as saturation of their electronic circuitry — specifically of their integrator (and/or of their output amplifier). This problem is discussed in greater detail in section (C), hereunder.

With Hall-sensor equipped instruments, such as the Magnograph

The total MA vs cumulative induced voltage relationship for the Magnograph is shown in Fig. 7. This instrument's design does not incorporate an integrator. Meaningful measurements can be performed throughout the instrument's entire 0 - 16 kg/m range, without the need for subdivisions.

All other, non integrator related, remarks as to the limited linearity range of the *'cumulative induced voltage (V)'* vs *'the wire-rope's linear density (kg/m)'* function do, however, apply.

(B) Practical consequences of incomplete magnetic saturation

With inductive-coil type instruments, such as the LMA-250

In case of the LMA-250 type instruments there are, at least, two practical considerations linked to a wire-rope's incomplete magnetic saturation, namely: (1) inaccurate %LMA chart-readings in case of substantial metallic area changes, and (2) attempts to determine the Total Metallic Area (TMA) of a wire rope, on the basis of a relationship between: (a) the different *induced voltages* (ΔV) caused by the same metallic mass change (ΔM), and (b) the *amount of total metallic mass inside the sensor-head* at the time of these ΔM changes.

(1) Inaccurate %LMA chart-readings

If the cumulative metallic area changes — say losses — are substantial, the chart readings will become less and less accurate as the losses mount in relation to the rope's 'calibrated' section, i.e., as the wire rope's metallic cross-sectional area becomes smaller and smaller. As an example, in case of test #9g, we noted the following:

(a) 2 1/4 in. assembly (12.90 kg/m), with calibrated gain setting of 1.46.

Step 'F' (Fig. 8): the 'true' metallic-area-losses (LMA) of 20.2%; 10.2%; and 6.2% occur at a sensor-head load of 12.90 kg/m; 10.29 kg/m; and 8.97 kg/m, respectively. The corresponding chart readings are (two tests): 21.8% and 20.6%; 13.2% (twice); 8.0% and 9.0%. The overall chart-reading error, therefore, is $\frac{43.0 - 36.6}{36.6} \times 100 = 17.5\%$, and $\frac{42.8 - 36.6}{36.6} \times 100 = 16.9\%$.

Step 'G' (Fig. 9): the 'true' LMA of 6.0%; 10.2%; and 20.2% occur at a sensor-head load of 12.90 kg/m; 12.09 kg/m; and 10.77 kg/m, respectively. The corresponding chart readings are: 6.2%; 10.5%; and 26.5%, with an overall error of 18.7%.

(b) 2 3/8 in. assembly (14.96 kg/m), with calibrated gain setting of 1.47.

Step 'D': the 'true' LMA of 13.6% and 5.4% occur at a sensor-head load of 14.96 kg/m and 12.92 kg/m, respectively. The corresponding chart readings are 13.6% and 6.4%, with an overall error of 5.3%.

(c) 2 1/2 in. assembly (16.07 kg/m), with calibrated gain setting of 1.48.

Step 'G' (Fig. 10): the 'true' LMA of 16.2% and 12.7% occur at a sensor-head load of 16.07 kg/m and 13.46 kg/m, respectively. The corresponding chart readings are (two tests): 16.0% and 16.5%; plus 15.5% and 16.0%, with an overall error, therefore, of 9.0% and 12.5%.

Step 'H' (Fig. 11): the 'true' LMA of 12.7% and 16.2% occur at a sensor-head load of 16.07 kg/m and 14.03 kg/m. The corresponding chart readings are 12.7% and 20.0%, with an overall error of 13.1%.

Step 'I' (Fig. 12): the 'true' LMA of 16.2%; 12.7%; and 8.2% occur at a sensor-head load of 16.07 kg/m; 13.46 kg/m; and 11.42 kg/m, respectively. The corresponding chart readings are 16.4%; 15.8%; and 10.8%, with an overall error of 15.2%.

Step 'K' (Fig. 13): the 'true' LMA of 16.2%; 12.7%; and 8.2% occur at a sensor-head load of 16.07 kg/m; 13.46 kg/m; and 11.42 kg/m, respectively. The corresponding chart readings are 15.8%; 15.2%; and 11.8%, with an overall error of 15.2%.

Step 'M' (Fig. 14): the 'true' LMA of 16.2%; 12.7%; and 8.2% occur at a sensor-head load of 16.07 kg/m; 13.46 kg/m; and 11.42 kg/m, respectively. The corresponding chart readings are 16.5%; 15.0%; and 12.7%, with an overall error of 19.0%.

Step 'N' (Fig. 15): the 'true' LMA of 4.4%; 5.1%; 8.2%; and 12.7% occur at a sensor-head load of 16.07 kg/m; 15.37 kg/m; 14.56 kg/m; and 13.24 kg/m, respectively. The corresponding chart readings are 4.4%; 5.5%; 8.5%; and 15.6%, with an overall error of 12.1%.

Step 'O' (Fig. 16): the 'true' LMA of 16.2%; 12.7%; 8.2%; and 5.1% occur at a sensor-head load of 16.07 kg/m; 13.46 kg/m; 11.42 kg/m; and 10.10 kg/m, respectively. The corresponding chart readings are 16.8%; 14.0%; 12.0%; and 6.0%, with an overall error of 15.6%.

Step 'P' (Fig. 17): the 'true' LMA of 2.65%; 4.37%; 5.05%; 8.22%; and 12.7% occur at a sensor-head load of 16.07 kg/m; 15.64 kg/m; 14.94 kg/m; 14.13 kg/m; and 12.81 kg/m, respectively. The corresponding chart readings are 2.68%; 4.65%; 5.98%; 9.86%; and 15.99%, with an overall error of 18.7%.

Re. the foregoing it is, however, important to note, that: (1) the total LMA examined in these examples exceeds losses that are likely to be encountered under practical operating conditions, (2) the chart-reading of the first LMA step, i.e., of the one for which the instrument was calibrated, was always as accurate as can be expected in practical terms, and (3) the overall error, even if substantial, was always positive, i.e., we were always erring 'on the safe side', with the actual losses being less than the recorded ones.

(2) Attempts at TMA measurement

It has been suggested elsewhere (e.g., in ref. 26) that it is possible to undertake Total Metallic Area (TMA) measurements of a wire rope's cross-section with inductive-coil type EM testers, rather than just relative %LMA ones. The premise, essentially, was based on the fact that the same amount of metallic mass change (ΔM) inside the sensor-head will produce different induced voltages (ΔV), as a function of the total metallic mass inside the head at the time of ΔM. This fact can not, however, be used for TMA measurements, either theoretically or pragmatically, because: (1) the process is much too inaccurate, even under the best of circumstances, and (2) for the same ΔM the induced voltage steps (ΔV) are the same (totally, in theory, and almost, in practice), as long as the total metallic mass inside the sensor-head is fully saturated magnetically (i.e., as long as this total mass is less than about 3-4 kg/m). Within this range ΔV is quite independent of the sensor-head load; it depends, solely, on the magnitude of ΔM, and on the instrument's LMA gain setting.

The author of the referenced paper suggests that: "*The best section of rope included in the NDT (assumed to be 100 per cent for the relative test) should be chosen for the absolute area determination*". Also: "*A steel rod (longer than the averaging length of the instrument) is placed on the outside of the rope. The rod represents an increase of approximately 5 per cent in the metallic area of the rope. The instrument should be calibrated for a metallic area equal to the metallic area of the rope plus the metallic area of the rod.*" Accordingly, the instrument is to be calibrated for the assumed rope area, plus the known area of the rod. The same process is later to be repeated, several times and at the same rope section, as time goes on. The TMA is to be gleaned from the different readings that are obtained at different times. However, this method involves calibrated gain settings; this, in turn, involves a *vicious circle* process, insofar as calibrated settings, in any shape or form, presuppose: (1) that the cross-sectional metallic area of the rope at the point of calibration, and in its present condition is known, exactly — the very information we lack — and (2) that by using calibrated gain settings one obtains accurate results. But even the latter assumption is shown to be in error, on occasion (e.g., see section (E) of this report).

The manufacturer's operation and maintenance manual does not refer to TMA measurements. Instead, the process described therein — while somewhat similar to the aforementioned one — is primarily intended for preparing, and/or for experimentally checking, the instrument's 'official' LMA calibration table. In this process the constant gain setting (G.S.) is to be an arbitrary one (the extreme setting of 10 is recommended). The process produces a proportionality factor — referred to as the *Machine Constant* 'K' — linking the amount of ferro-magnetic mass change (ΔM) with the corresponding amount of induced voltage change (ΔV). 'K' is expressed in $\frac{V}{in^2}$ by the manufacturer, with in^2 being the cross-sectional area of the 'thin' steel rod whose removal/insertion (thus causing ΔM) produces 'V'; we prefer $\frac{V}{kg/m}$ instead of $\frac{V}{in^2}$. The same 'thin' rod is removed/inserted alongside a whole gamut of total masses — ranging, say, from 0 kg/m, i.e., from an empty sensor head, to some 16 kg/m, i.e., to the head's maximum capacity — while the instrument's LMA gain setting is kept constant.

The manufacturer suggests that the resulting relationship between 'K' and the total mass in the sensor-head is a linear one (Fig. 18a). The reported results (Fig. 18b, test series #9c) show this not to be so. In this instance 3-ft long steel rods, once a $\frac{1}{16}$ in., and once a $\frac{23}{64}$ in. one, were removed from alongside bundles of steel rods (instead of wire ropes, as recommended by the manufacturer). These rods represented a range of sensor head loadings, in kg/m. The gain-setting was maintained at 10, throughout the tests. As may be seen, the induced voltage readings along the $\frac{1}{16}$ in. curve varied by some 11% (at most) in the 0-5 kg/m head-load range, and by some 56% along the range of heavier head-loads (i.e., along the range of incomplete magnetic saturation). In case of the $\frac{23}{64}$ in. curve the corresponding decline was some 42% along the incomplete saturation range, while for the lighter head-loads the induced voltages could not be established, because they exceeded the output-amplifier's saturation level of some 4.3 V.

Additional results are illustrated in Fig. 19. These are a summary of data 'standardized' for a gain setting of 1, as obtained by test series #9a, #9b, #9c, #9d, #9h, and #10a. In a few cases, as discussed in section (C) hereunder, we established the required ΔV to $G.S.$ ratios exactly (e.g., see Fig. 26). In general, though, this was done by simply altering the recorded ΔV values in the ratio of: *'actual dial setting number used'* to *'1'*. We know that this produces inaccurate results, but at this time we do not, as yet, have the necessary accurate information as to how each dial setting affects the relevant ΔV. In any case, the results of Fig. 18b are reconfirmed in Fig. 19: we see a fairly linear, gently sloping, ΔV vs. 'total mass' function as long as this total mass is magnetically almost fully saturated (say up to about the 5 kg/m mark), and a much more rapid decline along the remaining, heavier sensor-head loading, range.

On reducing the given results to the suggested *Machine Constant* basis (with kg/m instead of in^2 as size indicator), for a dial setting of 1, we obtained:

(1) a 'K' of 0.914 $\frac{V}{kg/m}$, as the average of the 17 empty head (i.e., 0 kg/m) readings, that included 'thin' rod sizes ranging from $\frac{1}{16}$ in. to $1\frac{5}{64}$ in. — with a corresponding *Standard Deviation* 'S' of a mere 0.0283 $\frac{V}{kg/m}$, while

(2) at the other extreme, i.e., for a total sensor-head load of some 16 kg/m, the corresponding 'K' value was 0.417 $\frac{V}{kg/m}$, as the average (at an 'S' of 0.0402 $\frac{V}{kg/m}$) of the 10 readings illustrated in Fig. 19, that included 'thin' rod sizes ranging from $\frac{1}{16}$ in. to $1\frac{5}{64}$ in. Finally,

(3) for the same 'thin' rod range, but at the 'discontinuity' point of a total head-loading of, say, 5 kg/m, the 'K' value was 0.863 $\frac{V}{kg/m}$, as the average (at an 'S' of 0.0383 $\frac{V}{kg/m}$) of the 7 readings illustrated in Fig. 19.

Consequently, the 'K' value function decreases by some 5.6% along the 0 kg/m to 5 kg/m total head-load range, and by some 51.7% along the remaining total load range.

The foregoing results clearly illustrate the fallacy of using this procedure as the basis for accurate TMA measurements, especially on the basis of a straight line relationship, as in Fig. 18a. However, the process has some merit, assuming that the foregoing tests are carried out for each individual instrument:

(a) carefully, and often enough, to assure ‘repeatability’,

(b) either at an arbitrary, constantly maintained, LMA gain dial setting (say of 1), or

(c) at a range of dial settings, all of which can, however, be accurately reduced to a single setting.

We see some merit in this process, insofar as it:

(1) helps to establish whether, or not, an instrument is in proper working order, and

(2) provides a small measure of TMA indication, assuming that the ‘thin’ rod is removed from a total metallic mass in the >4-5 kg/m, i.e., in the steeply dipping, graph range.

In practice foregoing point (2) most likely obtains, because:

(a) stranded ropes of about $1\frac{3}{8}$ in., and larger, as well as locked-coil ropes of about $1\frac{1}{8}$ in., and larger, weigh more than, about, 4.6 kg/m, and

(b) a majority of currently used mine-shaft wire-ropes in Canada are in the $1\frac{3}{8}$ in., plus, category (see ref. 2).

Even in this case, though, it seems advisable, on the basis of the abovenoted shape of the graphs in Fig. 19, that one use the largest ‘thin’ rod size that available space alongside the wire-rope will permit.

With Hall-sensor equipped instruments, such as the Magnograph

We have not, as yet, undertaken a detailed series of tests with the Magnograph, to parallel the ones discussed in point (1) of the foregoing section for the LMA-250 instrument (i.e., the case of substantial %LMA losses). We shall do so in due course. We have, however, tested the Magnograph with metallic area losses of up to 14%. These results are discussed in section (E) of this report (Figures 29 and 30). Moreover, the putative influence of incomplete magnetic saturation is also noted later (see section (E), Figures 31 and 32).

As for the previous point (2), namely TMA measurements, this presents no problem to EM instruments equipped with Hall-sensors. In case of the Magnograph, as an example, the calibration diagrams prepared by the manufacturer for each instrument individually (see sample in Fig. 3 of ref. 17) provide the sought after information, namely a rope's current kg/m parameter at the point of instrument calibration. As illustrated in our Fig. 7, the latter parameter can be read off the relevant diagram after the LMA signal has been zeroed by adjusting the LMA Zero Potentiometer-dial the required amount. We checked a few of these settings, and found a satisfactory correspondence between these and the rope's true kg/m parameter.

(C) Saturation of the electronic circuitry — integrators

With inductive-coil type instruments, such as the LMA-250

An essential component of the LMA signal-circuit of EM instruments with inductive-coils is their integrator. Operators of these types of testers must be aware of the limitation this design component imposes upon their specific test-instrument, namely, upon the maximum range of cumulative metallic mass changes that they are able to meaningfully measure. In this report this limit was measured by: (1) first adjusting the LMA Gain Potentiometer dial-setting (G.S.) to a value (say 0.5, or 1) low enough to ensure that, even with the head completely filled with metal, the cumulative induced voltages will not exceed the design limitations of the instrument's output amplifier — some 4.1 V in our case, and (2) then inserting into the sensor-head, one at a time, more and more 3-ft long steel rods, until either the head was replete, or the integrator was saturated.

The initial such tests (numbered tests 1 through 8) of March, 1990, involved the use of mock-up assemblies. The 1991 series of tests (such as #9h, and #10a) did not make use of mock-up assemblies. However, they did involve the same operator as the 1990 tests, as well as the same LMA-250 sensor-head, but with a different instrument console.

In tests #1 through #5 the small mock-up assembly was used. This limited the amount of metallic mass that could be inserted into the sensor-head to some 1.7 kg/m (Fig. 20) — an insufficient amount to bring about saturation of the integrator. Therefore, these results are not discussed here, but rather later, in the 'Repeatability' section of this report. In tests #6 through #8, though, up to some 4.8 kg/m of metal rods could be inserted into the large mock-up assembly. These results are illustrated in Fig. 21 (tests #6 and #7) and Fig. 22 (test #8). In Figures 21a and 22a we illustrate the cumulative induced voltages, as the metallic mass in the sensor-head is being increased/decreased, while in Figures 21b and 22b the individual induced voltage steps are recorded, as the rods are being inserted/removed. Finally, in Figures 23 and 24, we illustrate the results of tests #10a and #9h, respectively.

Concerning Fig. 21 we noted the following:

(1) there is no difference between the results of tests #6 and #7, i.e., the tests are 'repeatable';

(2) the instrument's integrator is saturated once the cumulative change in the amount of metallic mass inside the head exceeds some 1.8 kg/m, with respect to the instrument's calibration level; this is seen to be so because there is no further increase in the induced voltage past some 0.95 V (a value well below the output amplifier's saturation level) once the head contains the limiting 1.8 kg/m cumulative metallic mass, and finally,

(3) addition of each rod induces, more or less, the same voltage step up to this 1.8 kg/m level, i.e., the relationship between total mass in the head vs total induced voltage is linear, as was to be expected under conditions of complete magnetic saturation.

We may add that once the integrator's saturation level (with respect to its 'calibration' level) has been established, it applies equally to both positive and negative cumulative metallic mass changes.

This 1.8 kg/m measurement limitation is of no practical consequence in case of operational conditions involving wire-ropes of small and medium sizes — say up to about 2 in. diameter in case of stranded, and some $1\frac{3}{4}$ in. diameter in case of locked-coil ropes. With these rope-sizes cumulative metallic mass decreases (not to mention increases) in excess of 1.8 kg/m — with respect to the instrument's 'calibration' level — are never to be expected under normal operating conditions. Not so with the greater than aforementioned rope-sizes.

For example, in case of a 16.7 kg/m rope size (such as a $2\frac{1}{2}$ in. diameter, 34×7 balance rope) a 1.8 kg/m loss represents an LMA of some 11%: a 'real-life' situation. Once this limiting loss-level has been encountered cumulatively along a rope, the situation is as follows:

(a) as long as the losses continue to mount, only the 11% limiting loss-level will be recorded, unchanged, as the sensor-head moves along the rope, but

(b) immediately the sensor-head encounters a better rope section, i.e., decreasing losses, the recorder-pen will start to record this fact. Unfortunately, however, this decrease in losses will now be added to the previously recorded 11% limit, rather than to whatever value the 'true' losses happen to have reached in the rope-section between the point where the 11% limit was first exceeded, and the point where rope conditions start to improve (i.e., where the LMA begins to decrease).

For example, let us assume that after the strip-chart pen recorded the limiting loss of 11%, the 'true' losses continuously increased to, say, 14%. At this point rope conditions improved. The pen immediately records this, but adds the appropriate movement not to the 14% level (which it failed to record in the first place) but to the limit-level of 11%. Consequently, all chart-readings from this point on are (14%–11%) = 3% less than what they really are. Thus the chart's original 0% reference level could, under the appropriate circumstances, also be raised by 3%. Moreover, the foregoing situation could, conceivably, arise more than once along a long, and large diameter, rope: hence, on each such occasion, the subsequent chart-readings will become, cumulatively, more distorted.

Concerning Fig. 22 we noted the following:

while in tests #6 and #7 an arbitrarily low LMA Gain Potentiometer dial-setting (G.S.) of 0.20 was used — to ensure that the integrator's saturation level (some 1.8 kg/m) was obtained before the output-amplifier reached its level of saturation (at about 4.1 V) — this was not so in case of tests #4 and #8 (Fig. 22). For test #8, as an example, the LMA Gain Potentiometer dial-setting was 1.32, reflecting the manufacturer's tabulated instructions for an initial sensor-head loading of 0.96 in^2 of metallic cross-sectional area. As may be seen, there is no further change of induced voltage, once the -4.3 V level is reached. The corresponding cumulative metallic mass change in the sensor-head is of the order of 1.76 kg/m, at which point 26 of the $\frac{1}{8}$ in. rods have been removed, in pairs. It is uncertain whether at this point both the integrator, as well as the output-amplifier have been saturated, or only one or the other. In any case, the maximum %LMA that can be recorded with this instrument set-up is in the order of 35.8% of the original 0.96 in^2 — which is representative, say, of a $1\frac{3}{8}$ in. (4.94 kg/m), or of a $1\frac{1}{2}$ in. (5.88 kg/m), 6×27, FS, FC, wire-rope — a more than adequate value for practical purposes.

In Fig. 22a we illustrate the cumulative induced voltages as a function of decreasing rope mass in the sensor-head. In Fig. 22b the individual voltage-steps are recorded, as the rods are gradually removed (in pairs) from the head. The non-linearity of the function in Fig. 22a is particularly obvious in Fig. 22b. Here there is an overall difference of some 23.6% between the first (.275 V) and last (.340 V) measurements, with a noticeable shift of about 8% at the 1 kg/m total loss point — i.e., at the 3.8 kg/m total head-loading point. These increases in the ΔV steps would be in line with our other results (e.g., see Fig. 19) if the mass in the sensor head were to be magnetically unsaturated. However, the head only contains some 4.8 kg/m at the outset of this test, i.e., a quantity just slightly in excess of the 3-4 kg/m we previously noted in section (A) as being fully magnetizeable. We are, therefore, unable to say why there should have been a 23.6% V overall change in the measured ΔV values. Interestingly, when we loaded the large mock-up assembly (rather than unloading it) to the point of integrator saturation at a total head-load of some 1.8 kg/m (Fig. 21b), the individual voltage steps appeared to be unchanging — as was to be expected.

We mentioned earlier that the integrator's saturation limit might differ from instrument to instrument, and would, therefore, have to be established individually. As an example: in the foregoing we discussed the cumulative 1.8 kg/m limit established during the 1990 series of tests. As a result of the 1991 tests (#9h and #10a) with the same LMA-250 sensor-head but with a different console, we noted a greatly increased limit. This is illustrated in Figures 23 and 24.

Concerning Fig. 23 (test #10a) we noted the following:

1. the strip-chart recorder's LMA signal setting was, consistently, 0.2 V/mm, resulting in a scale of 1.0 V per major chart-division;
2. the LMA Gain Potentiometer dial-setting was 1 for steps 1 through 14, and 0.5 for steps 15 through 17;
3. the test involved rod sizes $\frac{13}{16}$ in. (step 13); 1.0 in. (steps 14 and 17); $1\frac{5}{64}$ in. (step 15); and $1\frac{7}{16}$ in. (step 16). The respective rod-weights were 2.64 kg/m; 3.95 kg/m; 4.59 kg/m; and 8.16 kg/m;
4. the test consisted of removing, and then reinserting these rods, one at a time, 10-12 times, from/into the otherwise empty sensor-head.

Apart from the quite remarkable 'repeatability' of the 10-12 measurements for each rod size, the test-results clearly showed that: (1) none of the induced voltages exceeded the output-amplifier's saturation level of some 4.1 V, and (2) the largest, i.e., $1\frac{7}{16}$ in., rod's insertion/removal alone resulted in integrator saturation. Here alone did we observe the tell-tale phenomenon described in the foregoing, namely that spurious LMA values are being recorded on reinsertion of the rod — i.e., in practical terms, when the instrument encounters an improved rope section. This is seen to be so because at the first rod reinsertion the 'true' 0%LMA reference level — in this case it also happened to be the 'calibration' (or 'reset') level — was shifted, in a positive direction, by exactly the amount which the pen was unable to record in a negative sense, due to the integrator's saturation.

In quantitative terms: at an LMA Gain Potentiometer setting of 0.5, the output amplifier recorded: (a) an induced voltage of -2.179 on the $1\frac{7}{16}$ in. rod's initial removal (from a head containing nothing else besides this 8.16 kg/m rod), and (b) an induced voltage of +1.603, on the occasion of first time rod reinsertion (into an empty sensor-head). Consequently, the first rod reinsertion resulted in an overall induced voltage step of 2.179 + 1.603 = 3.782 V — with the 11 subsequent rod insertions into the empty head producing (on an average) voltage steps of $\overline{X} = 3.752$ V, at a Standard Deviation of S = 0.00706 V. Similarly, the first time the rod was removed (*nota bene*, from a head containing this rod alone) without the integrator being saturated, the induced voltage step was 1.603 + 2.153 = 3.756 V — with the 11 subsequent rod removals resulting (on an average) in steps of $\overline{X} = 3.748$ V, at a Standard Deviation of S = 0.00554 V. It follows that $\frac{3.75\ (V)}{8.16\ (kg/m)} = 0.46\ (\frac{V}{kg/m})$, with an LMA Gain Potentiometer dial-setting of 0.5. Consequently, the initial limiting voltage of -2.179 means that, in this case, the electronic circuit of the integrator was saturated by a cumulative loss-of-metallic-area (LMA) of $\frac{2.179\ (V)}{0.46\ (V\ per\ kg/m)} = 4.742$ kg/m. It will be noted (Fig. 23) that removal/reinsertion of the $1\frac{5}{64}$ in. (4.59 $\frac{kg}{m}$) rod in step #15 did not, as yet, cause integrator saturation.

We may add that at the point of saturation the integrator's voltage can be assumed to be the same as the known saturation voltage of the output amplifier, namely some 4.1 V.

In the foregoing example the integrator's saturation limit was established with a sensor-head that was empty both after the $1\frac{7}{16}$ in. rod's removal, and before its reinsertion. This situation is of theoretical, but not of practical significance, because under operational test conditions the head is never empty. Practical situations were, however, simulated, *inter alia*, in test #9h (Fig. 24).

Concerning Fig. 24 (two runs) we noted the following:

in this case — with an LMA Gain Potentiometer dial-setting of 1, and an LMA scale of 1.0 V/major chart-division — a $1\frac{7}{16}$ in. rod was: (a) first added to an empty sensor-head, (b) removed, when the head was replete with 15.82 kg/m of metal, and (c) again added, when the head contained 7.66 kg/m of metal. In cases (a) and (c) the recorder-pen was pushed beyond the output-amplifier's/integrator's 4.1 V saturation-limit. However, step (b) yielded meaningful results. In this case we noted that removal of 8.16 kg/m from a total metallic mass of 15.82 kg/m resulted in induced voltage steps of 4.311 (first test) and 4.360 (second test) — as compared to the 3.75 V (Fig. 23, test

#10a) when the same mass is added to an empty head (or removed from one which contains this rod alone).

However, in order to meaningfully compare the results obtained with different gain settings (0.5 in test #10a, and 1 in test #9h), and with different amounts of metallic mass inside the sensor-head (empty in test #10a, and containing up to 15.8 kg/m in test #9h), one must know the relationship between the induced voltages and: (a) the corresponding LMA Gain Potentiometer dial-settings, and (b) the corresponding metallic mass loading of the sensor-head. Some of these relationships are described elsewhere in this report. Knowing them, we can say that: (1) in case of an empty sensor-head a cumulative LMA (whether positive or negative) — with respect to the instrument's calibration level — of some 4.74 kg/m will saturate the integrator, and (2) in case of a head containing some 15.8 kg/m of metallic mass — such as, for example, a 2 - $2\frac{1}{8}$ in. FLC hoist rope — saturation will occur in case of a cumulative LMA of about 7.72 kg/m. The foregoing values represent the extremes. In case of head-loadings in between these two, integrator saturation will occur within the cumulative metallic mass change-range of 4.74 - 7.72 kg/m. As an example: in case of head-loadings of about 10.8 kg/m (Fig. 17); 9.3 kg/m (Fig. 14); and 11.2 kg/m (Fig. 15), integrator saturation was seen to occur at a cumulative LMA value of some 6.8 kg/m; 7.0 kg/m; and 7.1 kg/m, respectively.

The question now needs to be addressed (Fig. 25) as to what the maximum cumulative ferro-magnetic mass changes (ΔM) might be, that can be meaningfully measured at this LMA-250 instrument's different LMA Gain Potentiometer dial-settings (G.S.) — i.e., measured without exceeding the integrator's and/or output amplifier's saturation level. In this context, however, we first needed to note that:

(1) both the integrator's and output amplifier's saturation level is in the order of 4.1 V to 4.3 V (see section (D) hereunder);

(2) a change in the gain-settings does not affect the induced voltage levels of the integrator. The latter depend only on the magnitude of ΔM, and on the total mass in the sensor-head at the time of ΔM; limiting values are 4.74 kg/m at an empty head, and 7.72 kg/m at a head-loading of 15.8 kg/m;

(3) a change in the instrument's gain setting (G.S.) does, however, affect the output amplifier's voltage level. While we have not, as yet, performed the necessary series of tests to obtain, accurately, the relationship between recorded induced voltages and the corresponding LMA Gain Potentiometer dial-settings, the problem was briefly examined in test #10a (Fig. 23), test #11 (Fig. 26), and test #9g (Figures

8 through 17). In test #10a, steps #14 and #17, using an otherwise empty sensor-head, the induced voltages due to the removal/reinsertion of a 1.0 in. (3.95 kg/m) rod were obtained, at dial-settings of 1 and 0.5, respectively. In step #14 the average voltage step on rod removal (repeated 10 times) was $\overline{X} = 3.6891$ V, at an S = 0.0300 V; and on a ten-fold rod reinsertion $\overline{X} = 3.6865$ V, at an S = 0.03593 V. The corresponding results in step #17 were: $\overline{X} = 1.9661$ V, at an S = 0.00314 V on rod removal; and $\overline{X} = 1.9637$ V, at an S = 0.00125 V, on rod reinsertion. Consequently, we found the following relationship on doubling the dial-settings with an empty sensor-head: $\frac{3.6891}{1.9661} = 1.8764$, on rod removal, and $\frac{3.6865}{1.9637} = 1.8773$, on rod reinsertion.

In case of test #11, steps #1 + #6, and steps #3 + #7 — involving the insertion/removal to/from a head (containing some 8.2 kg/m of metallic mass) of a $\frac{29}{64}$ in. (0.820 kg/m) steel rod — somewhat similar ratios were obtained, namely of $\frac{14.8}{8} = 1.85$, and of $\frac{11.0}{5.8} = 1.89$, respectively, on doubling the LMA Gain Potentiometer dial-settings. This test also demonstrated that should an operator set an LMA incorrectly, and later — by some means or other — realize this mistake, the original chart-readings can still be of use. They must, however, be appropriately modified. E.g., if, say, a dial setting of 1.4 had been used instead of the correct 0.88 one, all chart-readings must be reduced by the appropriate factor. The latter must, however, first be established by tests such as test #11.

As a result of test #9g we could compare, *inter alia*, the induced voltages that arose on removing a $\frac{29}{64}$ in. (.811 kg/m) rod from rod assemblies representing a 2.0 in.; a $2\frac{1}{8}$ in.; a $2\frac{1}{4}$ in.; a $2\frac{3}{8}$ in.; and a $2\frac{1}{2}$ in. wire-rope, with corresponding LMA gain settings of 1.67; 1.46; 1.47; and 1.48, respectively (see Appendix 2 for details). This test confirmed the abovenoted results, namely, that the ratio of two different gain settings does not equal the ratio of the thus induced voltages. In fact, in case of test #9g we found that the dial-setting ratios were, mostly, less than the corresponding induced voltage ratios. As an example, in case of: (1) dial-settings 1.67/1.57 = 1.064, the corresponding voltage ratio was 0.90/0.93 = 0.97, (2) for 1.57/1.46 = 1.076 the voltage ratio was .81/.60 = 1.35, (3) for 1.57/1.47 = 1.07 the voltage ratio was .81/.65 = 1.25, and (4) for 1.67/1.48 = 1.13 the voltage ratio was .90/.65 = 1.5.

We can now construct Fig. 25.

Curve α of Fig. 25 illustrates the different G.S. values, as a function of the total sensor-head loads at the point of instrument calibration, that must be used in order to obtain accurate chart-readings. These settings are in the 1.27 - 9.8 range. They can either be read off the manufacturer's relevant tabulation (α_2), or else be checked-out, independently, by tests such as the ones numbered 9b and 10 (α_1).

Curve β of Fig. 25 illustrates the maximum %LMA that can be meaningfully measured with the LMA-250 in question, at each tabulated G.S. Since we did not have all the information required for accurately establishing β, we approximated this curve by noting the following:

(a) at the heaviest tabulated head-load of some 17.61 kg/m (at a G.S. of 1.27) the maximum permissible LMA (or ΔM) is about 7.72 kg/m (at a G.S. of 1), which is, say, $\frac{7.72\times 1/1.27}{17.6} \times 100 = 34.5\%$ of the calibrated head-loading; while

(b) at the lightest tabulated head-load of some 1.11 kg/m (at a G.S. of 9.8) the maximum permissible LMA (or ΔM) is about 4.8 kg/m (at a G.S. of 1), which is, say, $\frac{4.8\times 1/9.8}{1.11} \times 100 = 44.1\%$ of the calibrated head-loading;

(c) we postulated that at intermediate G.S. values the general shape of curve β will resemble that of curve α.

As illustrated by curve β of Fig. 25, the maximum measureable %LMA values, within the tabulated G.S. range, are sufficiently wide ranging to be of little concern in practice. They must, however, be established for each inductive-coil type instrument, individually.

As for the $0 \leq$G.S.≤ 1 range, where $V_{(output\ amplifier)}$ is $\leq V_{(integrator)}$, the maximum permissible ΔM values that can be meaningfully measured are bracketed by 7.7 kg/m (for a sensor-head load of 15.8 kg/m), and by 4.74 kg/m (for an empty sensor-head). Along the remaining $1 \leq$G.S.≤ 9.8 range one may postulate, as an inaccurate but first approximation approach, that the foregoing borderline ΔM values decrease in the ratio of 1:G.S.

With Hall-sensor equipped instruments, such as the Magnograph

These instruments do not incorporate integrators. Consequently, none of the foregoing, integrator related, limitations apply to these testers. Also: the ***induced voltage*** to ***gain dial-setting*** ratios were available, had they been needed.

(D) Saturation of the electronic circuitry — output amplifiers

With inductive-coil type instruments, such as the LMA-250

We found the saturation level of the LMA-250 instrument's output amplifier to be in the order of 4.1 V to 4.3 V — a value large enough to be of little practical concern. This level, and its influence upon specific test requirements, must, however, be established for each instrument, individually.

To determine, *inter alia*, the output amplifier's saturation level, the manufacturer's tabulated gain settings were used. A case in point is test #9g. Here the gain setting was 1.48, in case of an initial sensor-head loading of seven steel rods with a total mass of 16.1 kg/m (representing a $2\frac{1}{2}$ in. wire rope). Step 'O' (Fig. 16) of this test involved, firstly, the step by step removal of all rods, except for the thickest ($1\frac{7}{16}$ in.) one, in the following order: (1) $\frac{13}{16}$ in. rod (2.61 kg/m); (2) $\frac{23}{32}$ in. rod (2.04 kg/m); (3) $\frac{37}{64}$ in. rod (1.32 kg/m); (4) $\frac{29}{64}$ in. rod (.811 kg/m); (5) $\frac{27}{64}$ in. rod (.703 kg/m); and (6) $\frac{21}{64}$ in. rod (.425 kg/m), and then, secondly, the step by step reinsertion of these selfsame rods, but in the reverse order to their removal. This process was repeated 30 times.

In step 'P' of test #9g (Fig. 17), with a gain setting of 1.48 (corresponding to a $2\frac{1}{2}$ in. wire-rope), the same six rods were again removed, and then reinserted, one at a time, but this time both removal and reinsertion occurred in the opposite order to the one listed for step 'O' (i.e., the $\frac{21}{64}$ in. rod was now removed first, etc., and the $\frac{13}{16}$ in. rod reinserted first, etc.). As in step 'O', the procedure was repeated 30 times. Recorder setting was 0.2 V/mm throughout, i.e., the instrument recorded 1 V (or 10% LMA) per major chart division.

These tests demonstrated the following, with a remarkable degree of 'repeatability':

(1) in step 'O' (Fig. 16) a maximum recorded cumulative negative voltage of some -4.3 V (on removal of the first three rods), and a shift above the 0%LMA instrument setting of (average after 30 repeats) $\overline{X} = +0.755$ V, at an S = 0.0349 V, after reinsertion of all six rods, and

(2) in step 'P' (Fig. 17) a cumulative -4.3 V maximum voltage, this time obtained on removal of all six rods, and an $\overline{X} = +0.787$ V, at an S = 0.0307 V (average of 30 repeats), again after reinsertion of all six rods.

From the foregoing, and the known kg/m of the rods used, it follows that in this case the recorded -4.3 V represents saturation of the output amplifier, and not of the integrator. The latter's saturation would, actually, have occurred at a calculated output amplifier voltage of some -5.3.

Incidentally, we determined the foregoing to be so, because: (a) the +0.787 V represents about 1.13 kg/m (coincidentally, as shown in Fig. 17, this is also the total mass of the two thinnest rods); (b) the six rods that were removed/reinserted represent a total of some 7.91 kg/m, and (c) the (7.91 - 1.13) = 6.78 kg/m represents some 5.3 V, because the recorded induced voltage is in the order of $\frac{1.589\ (V)}{2.04\ (kg/m)} = 0.779\ \frac{(V)}{(kg/m)}$ (note removal of the $\frac{23}{32}$ in. rod in step 'P'). It may also be noted that in step 'P' integrator saturation occurred on removing the $\frac{13}{16}$ in. (2.61 kg/m) rod from a total head-loading of some 10.8 kg/m; in step 'M' it occurred on removing the $\frac{27}{64}$ in. (.703 kg/m) rod from a total head-load of some 9.3 kg/m (calculated output-amplifier voltage $\approx$5.7); and in step 'N' it occurred on removing the $\frac{13}{16}$ in. (2.61 kg/m) rod from a total head-load of some 11.2 kg/m (calculated output-amplifier voltage $\approx$5.1).

We confirmed that the output amplifier's saturation level is about 4.3 V with a more recent, and simpler, series of tests as well. In this case we inserted the $\frac{1}{2}$ in. × 8 ft long, 6×26 rope sample, referred to in the 'Test Parameters' report section, into the closed sensor-head. LMA gain setting was 10, and balance setting 5.2. Rope insertion itself resulted in an induced voltage of 3.26. On subsequently adding, and then removing, five $\frac{1}{8}$ in. × 3 ft long steel rods to/from the rope inside the head, one rod at a time, we obtained the following cumulative voltages: 3.58; 3.90; 4.23; 4.37; and 4.37 (on rod insertion), and 4.37; 4.25; 3.93; 3.61, and 3.29 (on rod removal). It follows that the output amplifier was saturated at 4.37 V — and not the integrator, because: (a) on rod removal, we obtained almost exactly the same voltages as had previously been recorded on rod insertion, and (b) the total metallic mass (the wire-rope, plus the five rods) inserted into the head only represented some 0.97 kg/m altogether, i.e., much less than is required for integrator saturation.

With Hall-sensor equipped instruments, such as the Magnograph

As discussed in the foregoing, the LMA-250 circuitry's saturation level was found to be 4.1 V - 4.3 V. Consequently, its internal supply voltage can be assumed to be ±5 V. Our Magnograph's internal supply voltage is known to be ±15 V. Moreover, the Magnograph is designed for an LMA gain setting of 10 mV/%LMA of chart-recording, vs the 100mV/%LMA of the LMA-250. Consequently, we consider output amplifier saturation to be of little, or no, concern when using the Magnograph.

(E) Calibrated LMA gain potentiometer settings, and corollary matters

With inductive-coil type instruments, such as the LMA-250

A tabulated list of dial-settings of the LMA Gain Potentiometer, as a function of the total metallic mass inside the sensor-head at the point of instrument calibration, is provided by the instrument's manufacturer. As noted in Appendix 2, an extensive series of tests was performed with the LMA-250 instrument, and its tabulated gain settings, *inter alia* so as to verify the accuracy of these settings. These tests included the ones numbered 4a, 4b, 8, 9b, 9e, 9f, 9g, 10b, and 11.

If correctly tabulated, and set by the operator, the ensuing %LMA strip-chart readings should equal the 'true' values. Unfortunately, this was not always the case. Consequently, it is advisable to prepare one's own calibrated dial-settings. The process is quite straightforward, as illustrated by the reported series of tests. A selection of the results is illustrated in Fig. 22 (tests #4 and #8) and Fig. 27 (test #10b). From these it will be noted — with the extreme -13.2% and -18.9% errors, obtained with the two largest 'rope sizes' of $2\frac{3}{8}$ in. and $2\frac{1}{2}$ in., respectively, not even included in Fig. 27 — that the manufacturer's tabulated list of gain-settings had to be altered, in order to obtain accurate %LMA chart-readings. While in this instance incorrect tabulations were, perhaps, responsible for this discrepancy, we must also caution, and emphasize, that these tests were undertaken with bundles of 3 ft long steel-rods, rather than with actual wire-ropes. But, on comparing results of tests #12 through #14 with #18 and #19 (Fig. 28), we see that tests with rods instead of ropes, even when of equivalent total mass, can produce somewhat different results, possibly because: (1) the wire ropes incorporate air pockets between the individual wires and strands, that are absent in case of the rods, and (2) the spatial distribution of the rods in the sensor-head does not match that of the strands in the ropes.

In fact, more recent tests — with a different LMA-250 sensor-head as well as console; different tabulated dial-settings; and with 8-ft long stranded wire-rope samples (see their listing in this report's section on 'Test Parameters') — did produce satisfactory results. In the latter case we first entered one of these rope samples into the closed head, and set the LMA gain to the corresponding value, as per the manufacturer's tabulation. Subsequently, we added several $\frac{1}{8}$ × 3-ft long steel rods, one at a time, to the rope-sample. We recorded the induced voltage steps at each rod insertion. Results were as follows:

(1) 2.0 in., 6×25 rope in head (with LMA gain of 1.65); at a 'true' metallic-area (MA) increase of .58%; 1.15% and 1.73% the corresponding 'chart-readings' (in actual fact, a conversion of the respective voltage readings) were: .53%; 1.10%; and 1.63%.

(2) 1 3/4 in., 6×25 rope in head (with LMA gain of 2.02); at a 'true' MA increase of .75%; 1.51% and 2.26% the corresponding 'chart-readings' were: .75%; 1.49%; and 2.21%, respectively.

(3) 1 1/2 in., 6×25 rope in head (with LMA gain of 2.66); at a 'true' MA increase of 1.03%; 2.06% and 3.08% the corresponding 'chart-readings' were: 1.04%; 2.05%; and 3.07%, respectively.

(4) 1 1/8 in., 6×25 rope in head (with LMA gain of 4.44); at a 'true' MA increase of 1.79%; 3.57% and 5.36% the corresponding 'chart-readings' were: 1.69%; 3.38%; and 5.07%, respectively.

With Hall-sensor equipped instruments, such as the Magnograph

The situation with these instruments is no different from the one described above for the inductive-coil type instruments, except that in this case the manufacturer usually provides diagrams (e.g., see Fig. 3 of ref. 17), rather than tables, for the proper setting of the LMA Gain Potentiometer as a function of the kg/m mass inside the sensor-head at the point of calibration. These settings were checked-out by two operators, independently, using both the small and large mock-up assemblies with steel rods, in tests #16 and #17. The results are illustrated in Figures 29 and 30. As may be seen, the %LMA chart readings are in good agreement with the 'true' values, as long as the gain was correctly set. This was so only in case of operator 'B'. Operator 'A' used incorrect settings, thus documenting our often expressed opinion as to the need for better, and more consistent, operator training.

As a corollary — paralleling our previous notes on test #8 (Fig. 22b) for the LMA-250 tester — we again observed a phenomenon that, at first sight, appears to be the result of incomplete magnetic saturation. This is illustrated in Figures 31 and 32 (tests #12, #13, and #14). Note here: (1) the decreasing ΔV steps as the total kg/m load in the head increases, and (2) the manifest difference in the ΔV values when loading: (a) the peripheral and (b) the central tubes.

(F) Repeatability, and corollary matters

We have often commented upon the remarkable degree of 'repeatability' — irrespective of the instrument that happened to be used — both in our many referenced reports, as well as in the foregoing sections of this report. In the latter context one may note, for example, such remarkable Standard Deviation (S) values as 0.00706 V; 0.00554 V; 0.00300 V; 0.00314 V; 0.00125V in case of 10-12 repeats, as well as 0.0349 V and 0.0307 V in case of up to 30 repeats, as obtained with the LMA-250 instrument. Remarkable repeatability is also demonstrated by the results of tests #1, #2 and #3 (Fig. 20), of tests #6 and #7 (Fig. 21), and of tests #4 and #8 (Fig. 22), again with the LMA-250.

As corollary observations we might again (as in section (C) before) note that in Figures 20 and 21 the *'cumulative induced voltage (V)'* vs. *'total mass in sensor head (kg/m)'* relationship was almost linear — as was to be expected within the range in which complete magnetic saturation obtains. Specifically, in case of Fig. 20, for example, the 45 mV per $\frac{3}{32}$ in. rod insertion was equally true: (1) whether the rod was the first, or the 49-th; (2) whether the mock-up was loaded symmetrically or non-symmetrically; and (3) whether the stepwise change of ferro-magnetic mass inside the sensor-head was positive or negative. Moreover, the end-result was, within practical limits, the same (some 2.22 V) whether the 1.7 kg/m mass (i.e., the $49\times\frac{3}{32}$ rods) was inserted into the closed sensor-head as a single unit (test #5a), or in 49 seperate and equal steps (tests #1 through #3). We must, however, also caution that the operators of inductive-coil instruments be aware of the entirely different results obtained by: (a) closing the sensor-head around the fully loaded mock-up (test #5b), or (b) by sliding the same mock-up into a closed head (test #5a). The latter process resulted in a meaningful value of 2.22 V, while the former produced the meaningless result of -1.02 V.

In case of Hall-sensor equipped instruments, such as the Magnograph, it makes no difference whether the head is closed around the wire-rope, or the rope is slid into a closed head. As to the 'repeatability' aspect of the results obtained with this type of tester, we refer to the satisfactory results of tests #12 through #15, as illustrated in Fig. 33.

CONCLUSIONS

The test results discussed in this report highlighted a number of areas in the domain of the EM testers' LMA signals that operators should be well aware of.

In case of inductive-coil equipped instruments, such as the LMA-250, we were particularly concerned with the consequences of integrator and/or output amplifier saturation. It was seen to occur at about 4.1 V - 4.3 V. This results in specific operational constraints, such as, for example, the maximum total change of some 7.7 kg/m that can be meaningfully measured in case of an initial sensor-head loading of some 16 kg/m. Whether, or not, this type of constraint needs to be of concern has to be established on a case by case basis.

While integrator saturation is the more likely limiting factor in case of large size wire-ropes (say of more than 2.0 inches), the instrument's LMA Gain Potentiometer dial-setting is the more likely controlling factor in case of smaller rope sizes. The overall picture is presented in Fig. 25.

Hall-sensor equipped instruments, such as the Magnograph do not involve the use of integrators. Any limits imposed by the latter are, therefore, eliminated. Also, the Magnograph's internal supply voltage is ±15 V, as compared to the ±5 V for the LMA-250. Its output amplifier is, therefore, unlikely to saturate, especially since its design is based on a value of 10 mV/%LMA, rather than the 100 mV/%LMA of the LMA-250 tester.

Incomplete magnetic saturation of the ferro-magnetic mass inside the sensor-head is an operational reality with any type of EM instrument. A number of consequences must, therefore, be examined, such as: (1) the situation with large-size ropes, in case of substantial metallic losses, and (2) the influence of defect locations — e.g., at, or near to, the rope's core.

Another, all pervasive, source of error is the possibility of inaccurate LMA Gain Potentiometer dial settings, either as a result of inaccurate calibration tables, or of human errors. A number of tests were undertaken to demonstrate the need for determining the correct gain-settings, and to show ways to achieve this.

A putative method of performing total LMA measurements with inductive coil type instruments — rather than just relative ones — was also examined, and shown to be in error. Total LMA measurements with instrument designs incorporating Hall-sensors, or their equivalents, are known to be both possible and accurate.

It might be relevant to recall at this point an earlier postulate of ours (ref. 7, p.8), namely, that a ±2% 'benchmark' error for the LMA chart-reading may be acceptable, in line with the ±4% acceptable error range established for the Loss-of-Breaking-Strength (LBS) estimates.

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REFERENCES

1. Geller, L.B.; and Udd, J.E. "How accurate are non-destructive-testing based estimates of mine shaft rope breaking-strength losses? — an update"; CIM Bull., 83, no. 944, pp. 47-50; December, 1990.

2. Geller, L.B.; Udd, J.E.; and Mitchell, E.W. "Comparative evaluation of mine-shaft wire-rope NDT instruments: a search for, and analysis of, background information — contribution to the Canada/USBM/Ontario MOL joint R&D program"; CANMET Division Report MRL 88-78, 139 pp; July, 1988.

3. Geller, L.B.; Anderson, G.L.; Miscoe, A.J.; and Mitchell, E.W. "The safety of mine-shaft wire-ropes — cooperative work by Canada and the U.S.A."; CANMET Division Report MRL 89-14, 28 pp; February, 1989.

4. Geller, L.B.; Udd, J.E.; Blanchard, R.; and Daniel, K.E. "About electro-magnetic wire-rope testing in New Brunswick mines, and related data"; CANMET Division Report MRL 89-40, 51 pp; October, 1989.

5. Geller, L.B.; and Rousseau, G. "Effect of trapped wire-rope debris upon an EM instrument's LMA chart-trace"; CANMET Division Report MRL 90-08, 29 pp; February, 1990.

6. Rousseau, G.; and Geller, L.B. "Étude des performances de deux instruments électromagnetiques pour détecter les défaults localisés (LF) dans les câbles d'acier"; CANMET Division Report MTL 91-33, 40 pp; April 1991 (in French).

7. Geller, L.B.; Rousseau, G.; and Poffenroth, D. "Canada/NB MDA project on mine-shaft rope testing; stranded ropes with artificial defects"; CANMET Division Report MRL 90-015, 117 pp; February, 1990.

8. Geller, L.B.; Poffenroth, D.; Udd, J.E.; and Hutchinson, D. "Canada/NB MDA project on mine-shaft rope testing; testing of 1 1/4 in., FLC, H.R. (our rope #4)"; CANMET Division Report MRL 90-044, 76 pp; May, 1990.

9. Geller, L.B.; Poffenroth, D.; Udd, J.E.; and Hutchinson, D. "Evaluation of EM rope testers: Canada/US joint work"; CANMET Division Report MRL 90-052, 24 pp; June, 1990.

10. Geller, L.B.; Poffenroth, D.; Udd, J.E.; and Hutchinson, D. "Canada/NB MDA project on mine-shaft rope testing; testing of 1 7/16 in., FLC, H.R. (our rope #5)"; CANMET Division Report MRL 90-053, 46 pp; June, 1990.

11. Geller, L.B.; Poffenroth, D.; Udd, J.E.; and Hutchinson, D. "Canada/NB MDA project on mine-shaft rope testing; testing of 1 7/8 in., 34×7, NR, T.R., (our rope #9)"; CANMET Division Report MRL 90-060, 48 pp; July, 1990.

12. Geller, L.B.; Poffenroth, D.; Udd, J.E.; and Hutchinson, D. "Canada/NB MDA project on mine-shaft rope testing; testing of 1 7/8 in., 34×7, NR, T.R., (our rope #12)"; CANMET Division Report MRL 90-069, 30 pp; July, 1990.

13. Geller, L.B.; Poffenroth, D.; Udd, J.E.; and Hutchinson, D. "Canada/NB MDA project on mine-shaft rope testing; testing of 1 1/2 in., 60×30, H.R. (our rope #7)"; CANMET Division Report MRL 90-071, 128 pp; August, 1990.

14. Geller, L.B.; Poffenroth, D.; Udd, J.E.; and Hutchinson, D. "Canada/NB MDA project on mine-shaft rope testing; testing of 1.000 in., H.R., (our rope #1)"; CANMET Division Report MRL 90-131, 43 pp; December, 1990.

15. Geller, L.B.; Poffenroth, D.; Udd, J.E.; and Hutchinson, D. "Canada/NB MDA project on mine-shaft rope testing; testing of 1.000 in., 6×27, FS, H.R., (our rope #2)"; CANMET Division Report MRL 91-001, 30 pp; January, 1991.

16. Geller, L.B.; Poffenroth, D.; Udd, J.E.; and Hutchinson, D. "Canada/NB MDA project on mine-shaft rope testing; testing of 1 3/4 in., 6×25, RS, H.R., (our rope #10)"; CANMET Division Report MRL 91-002, 30 pp; January, 1991.

17. Geller, L.B.; and Kitzinger, F. "Techniques to better exploit the possibilities of wire-rope testing with electro-magnetic instruments"; CANMET Division Report MRL 91-003, 70 pp; January, 1991.

18. Rousseau, G.; and Geller, L.B. "Analysis of the NDT reports relating to the June 23, 1990, hoist-rope failure in Elliot Lake, Ontario"; CANMET Division Report MTL 91-34, 76 pp; June, 1991.

19. Geller, L.B.; and Udd, J.E. "NDT of wire ropes with EM instruments — an examination of operational conditions in Canada"; CANMET Division Report MRL 91-019, 23 pp; March, 1991.

20. Geller, L.B.; Poffenroth, D.; Udd, J.E.; and Hutchinson, D. "Canada/NB MDA project on mine-shaft rope testing; testing of 7/8 in., 1×90, L.C., H.R., (our ropes #13 & #14)"; CANMET Division Report MRL 91-044, 50 pp; April, 1991.

21. Geller, L.B.; Poffenroth, D.; Udd, J.E.; and Hutchinson, D. "Canada/NB MDA project on mine-shaft rope testing; testing of $1\frac{3}{16}$ in., 1×136, FLC, H.R., (our rope #3); CANMET Division Report MRL 91-054, 25 pp; May, 1991.

22. Geller, L.B.; Poffenroth, D.; Udd, J.E.; and Hutchinson, D. "Canada/NB MDA project on mine-shaft rope testing; testing of $1\frac{7}{16}$ in., 1×176, FLC, H.R., (our rope #6); CANMET Division Report MRL 91-055, 27 pp; May, 1991.

23. Geller, L.B.; Poffenroth, D.; Udd, J.E.; and Hutchinson, D. "Canada/NB MDA project on mine-shaft rope testing; testing of $1\frac{5}{8}$ in., 18×7, NR, T.R., (our rope #8; CANMET Division Report MRL 91-057, 18 pp; June, 1991.

24. Geller, L.B.; Poffenroth, D.; Udd, J.E.; and Hutchinson, D. "Canada/NB MDA project on mine-shaft rope testing; testing of $2\frac{1}{4}$ in., 34×7, NR, T.R., (our rope #11; CANMET Division Report MRL 91-062, 36 pp; June, 1991.

25. Geller, L.B.; Rousseau, G.; and Poffenroth, D. "Canada/NB MDA project on mine-shaft rope testing; $1\frac{11}{16}$ in., 33×7, NR ropes with artificial defects (our ropes 'C' and 'D')"; CANMET Division Report MRL 91-073, 36 pp; July, 1991.

26. Poffenroth, D. "Electromagnetic testing — wire ropes"; *Wire Industry*, pp. 601-608; August, 1990.

APPENDIX 1

Test set-ups

Figures 1 through 5, inclusive

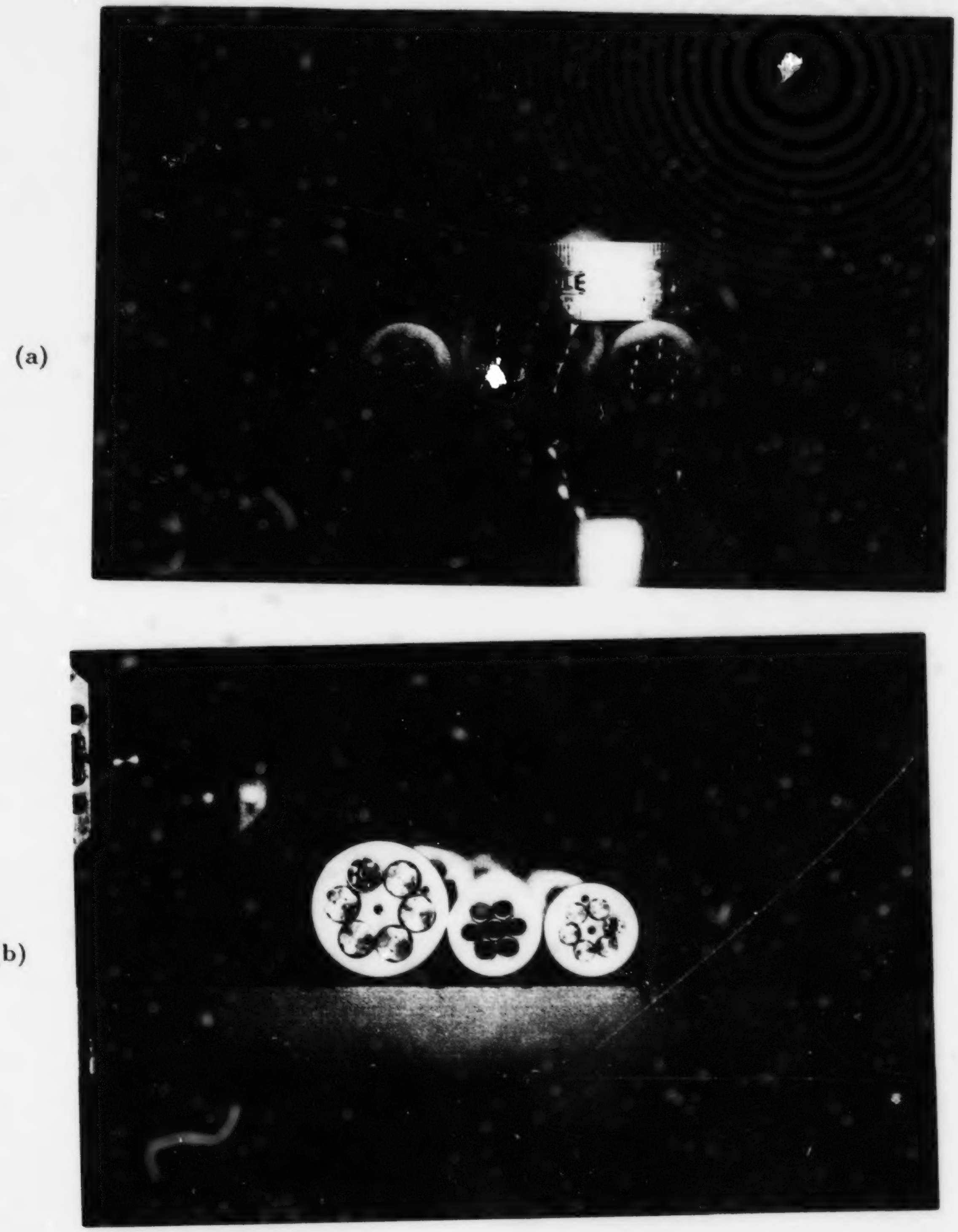


Fig. 1 — Mock-ups used for analysing the EM testers' LMA and LF (see ref. 6 for latter) channel signals

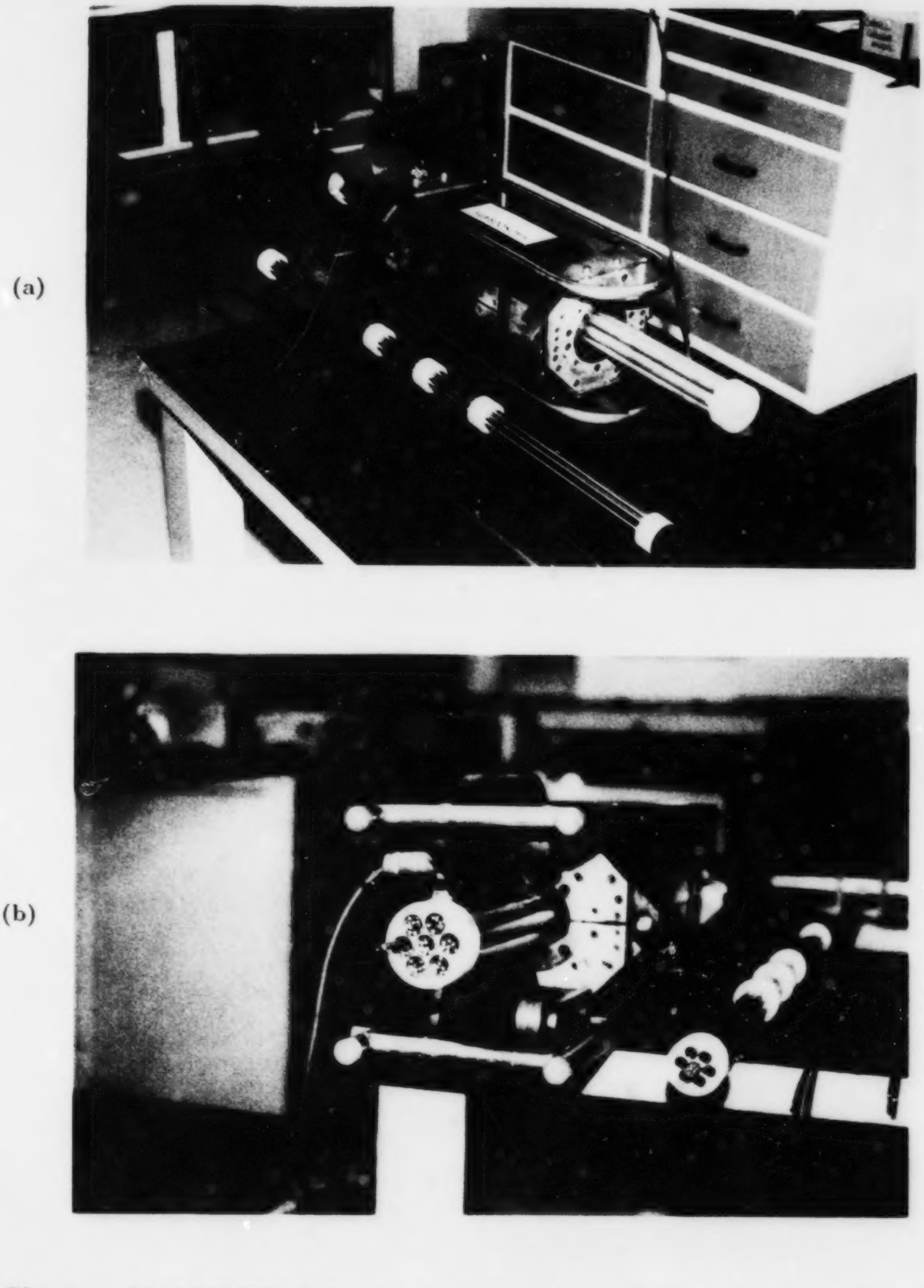
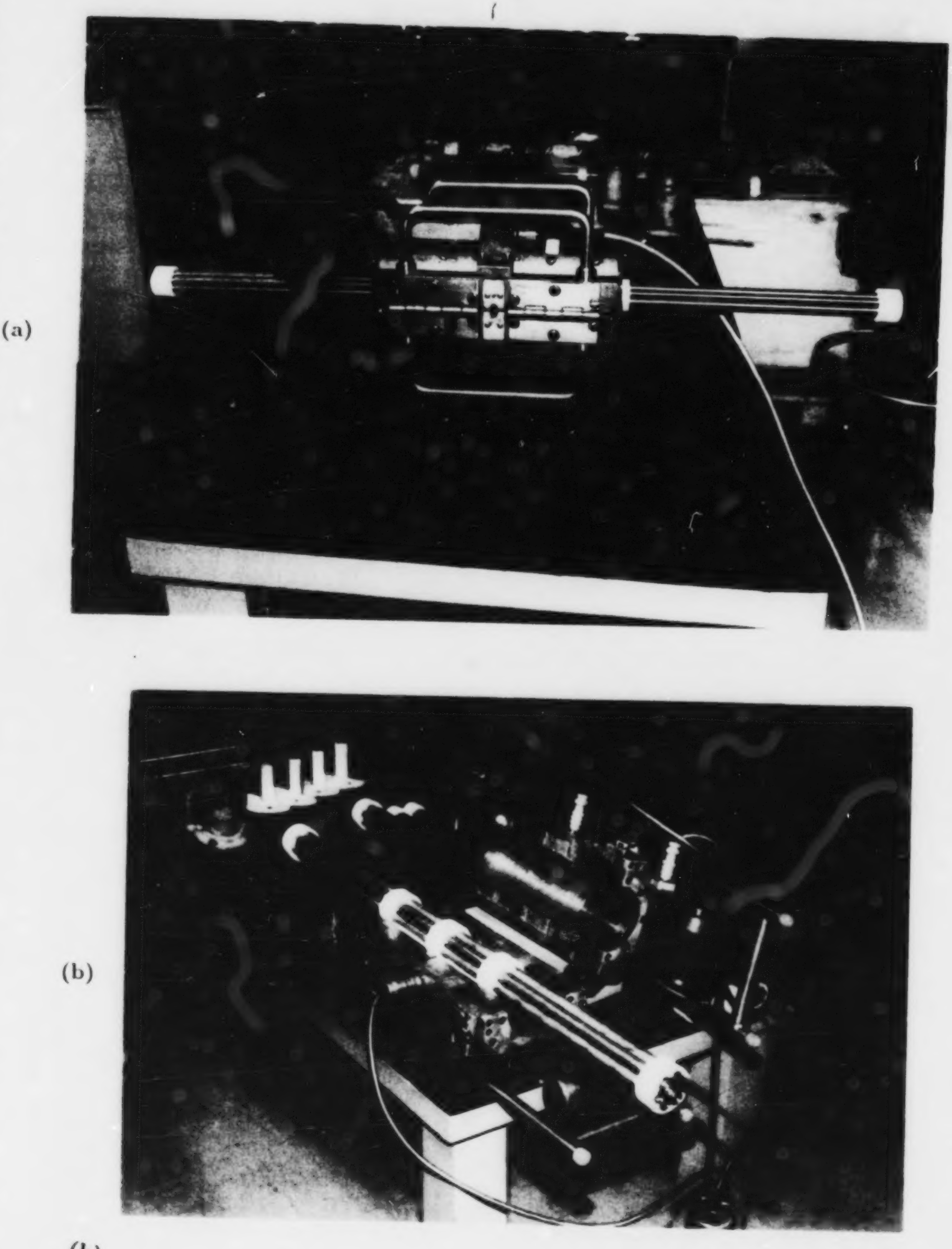


Fig. 2 — MAGNOGRAPH with 7-tube mock-ups (large and small) used for LMA signal analysis



(b)

Fig. 5 — (a) LMA-250, and (b) MAGNOGRAPH (note its inserts for different rope sizes at back of table) with small mock-up

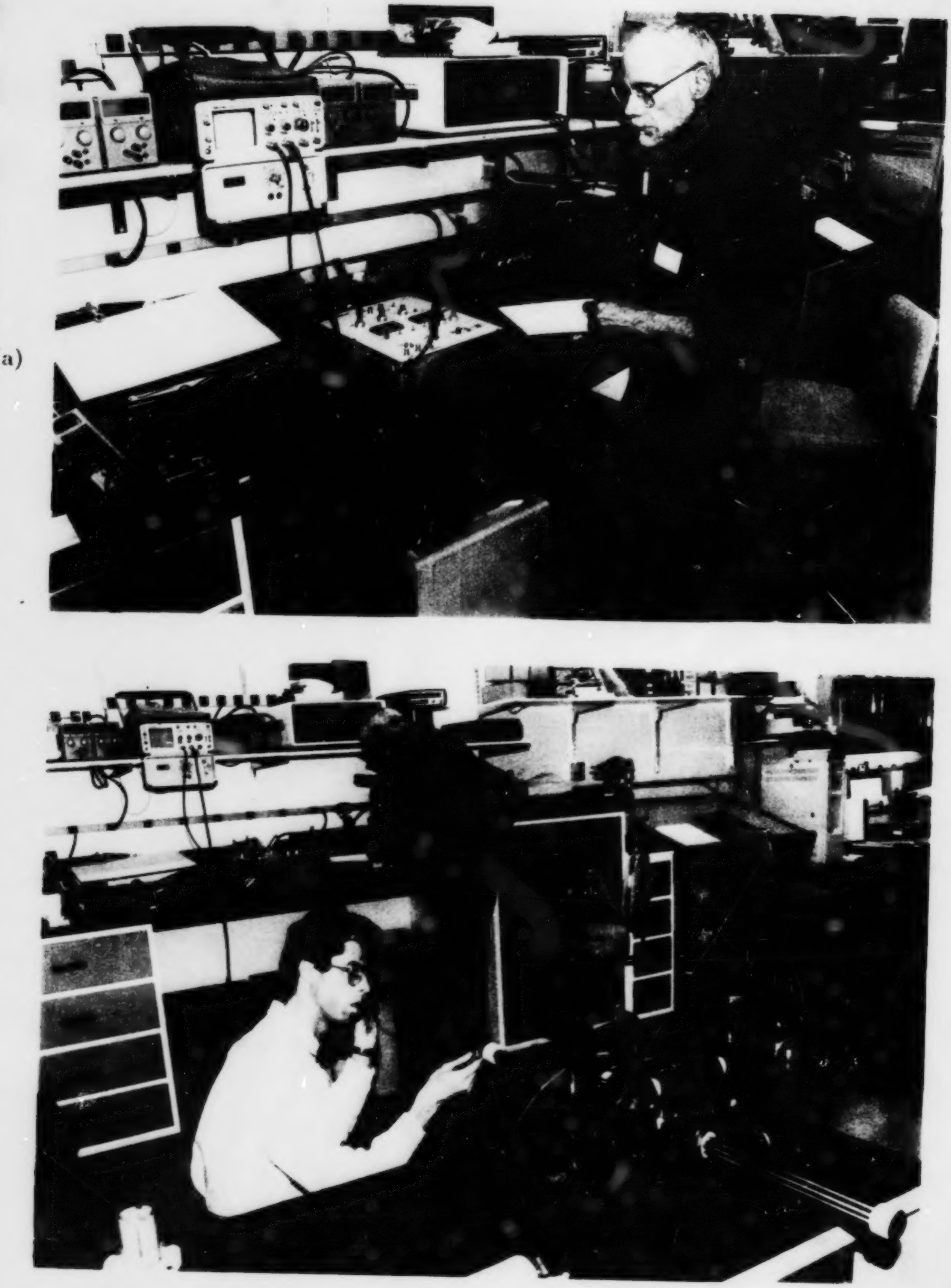


Fig. 4 — LMA-250, with signal testing in progress

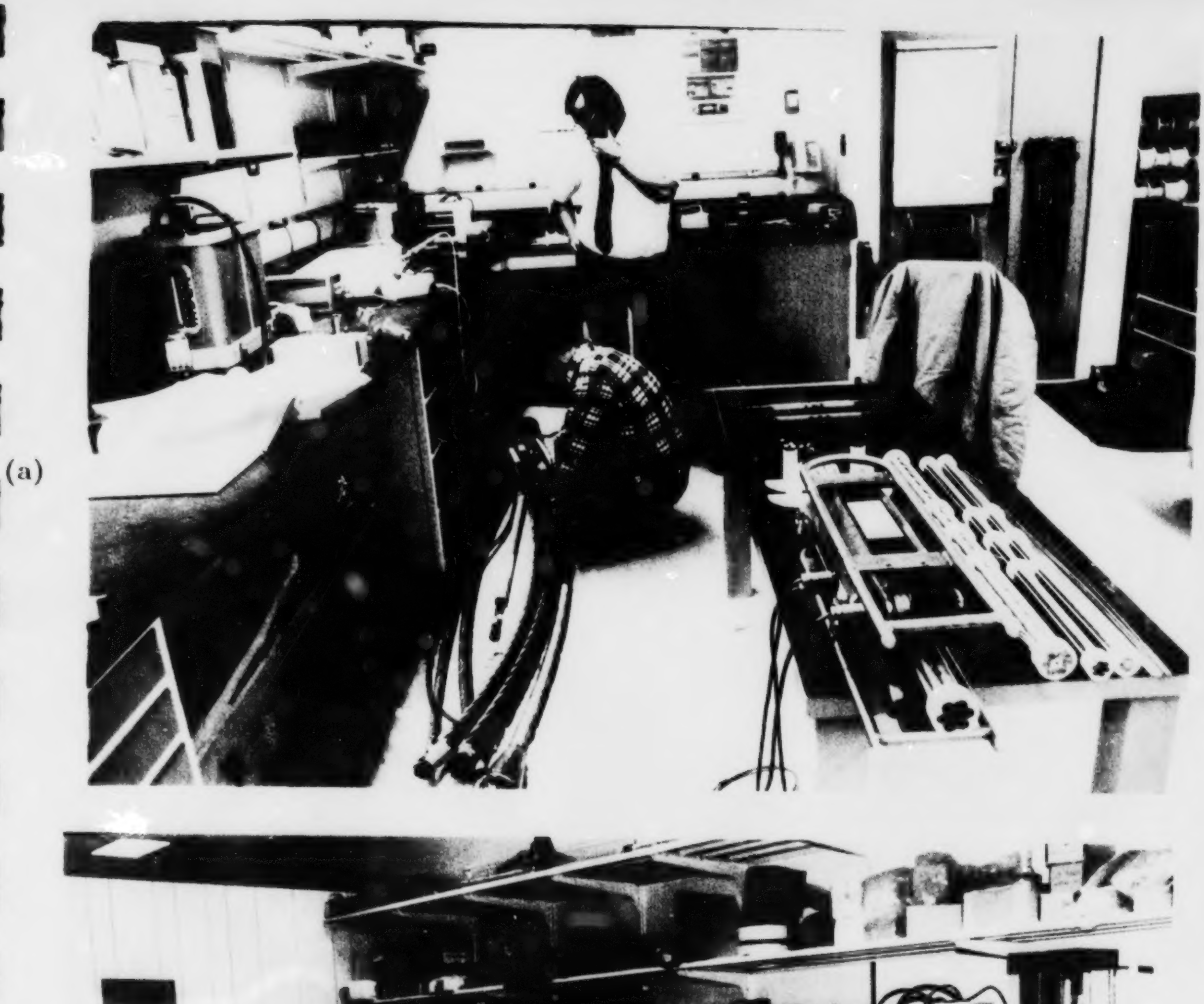


Fig. 5 — MAGNOGRAPH, with (a) six wire-rope samples (on the floor) and mock-ups (all four, on the table), and (b) LMA testing, using wire-ropes, in progress

APPENDIX 2

Test details

The following series of tests was performed:

With the LMA-250 instrument

A.) Tests involving the mock-up assemblies — tests #1 through #8

Test #1

Use the $1\frac{1}{4}$ in. small mock-up assembly. Insert it, while still empty, into the closed sensor-head, and set the instrument's LMA Gain Potentiometer at an arbitrary value of 0.54 (merely chosen to ensure that the induced voltage does not rise inordinately as the test progresses). Maintain this gain setting throughout the test. Turn on the power. Reset the LMA signal to its reference level by pushing the LMA reset button. Read, and record the voltage on the meter connected to the tester's LMA Output Jack.

Proceed to symmetrically fill the mock-up assembly's seven 3/8 in. diameter tubes with 3/32 in. steel rods, by placing in each adjacent peripheral tube one of these rods, and finally one into the central tube. Observe, and record, the voltage changes each time a rod is added. Continue this process until all seven tubes are full, i.e., until each contains seven steel-rods. After the mock-up is replete with 49-$\frac{3}{32}$ in. steel rods, proceed to remove one rod from each tube, in the reverse order used for filling them. Again observe, and record, the voltage changes each time a rod is removed. Continue this process until all rods have been removed.

Test #2

Check 'repeatability' by performing test #1 a second time, exactly as it was done the first time.

Test #3

Repeat test #1, again with the same constant LMA Gain Potentiometer setting of 0.54. However, instead of symetrically filling the small mock-up assembly, now do so non-symmetrically. This is done by first completely filling one of the peripheral 3/8 in. tubes with 7-$\frac{3}{32}$ in. rods, before doing the same with its neighbour, etc., until all six peripheral tubes are filled. Only then is the central tube to be filled. Read and record the voltage changes each time a rod is added.

Test #4a

Completely fill all seven tubes of the small mock-up assembly with 3/32 in. rods (i.e., with 49 rods altogether). Insert this assembly into the open sensor-head, and then close the head around it. Adjust the instrument's LMA Gain Potentiometer setting as appropriate for the amount of metal initially inside the sensor-head, as per the manufacturer's relevant instructions (e.g., see Table 2 of ref. 26) — i.e., to 3.62 in our case, for a total metallic cross-sectional area of 0.333 in^2. Maintain this setting throughout the test. Push the LMA reset button. Remove, consecutively, one rod from each of the adjacent six peripheral tubes, and finally from the central tube. Then, in the same manner, remove a second rod from each tube, etc., until all rods have been so removed. Observe, and record, the voltage changes as each rod is removed.

Test #4b

Proceed as in test #4a, except that at start-up the small mock-up assembly only contains 42-$\frac{3}{32}$ in. rods (instead of 49), because only the peripheral tubes are replete with rods, while the central 3/8 in. tube is left empty. Consequently, the LMA Gain Potentiometer is set to 4.23 (instead of 3.62) throughout the test, in line with the manufacturer's instructions for the case when the sensor-head initially contains a total metallic cross sectional area of 0.2853 in^2.

Test #5a

Completely fill the small mock-up assembly with 49-$\frac{3}{32}$ in. rods. Adjust the LMA Gain Potentiometer setting to the same arbitrary value of 0.54 as had been used for tests #1 through #3. Maintain this setting throughout the test. Push the LMA reset button. Now insert the small mock-up assembly into the closed sensor-head. Observe, and record the voltage change. Remove the mock-up assembly from the closed sensor-head, and again observe, and record, the ensuing voltage change.

Test #5b

Proceed as in test #5a, except that this time the small mock-up assembly is inserted into an open sensor-head, which is then closed, subsequently, around it.

Test #6

Use the 1$\frac{7}{8}$ in. large mock-up assembly. Insert it, while still empty, into the open sensor-head and close the latter around it. Set the instrument's LMA Gain Potentiometer to an arbitrary value of 0.20 — this setting merely being chosen to ensure that the induced voltage will not rise inordinately as the mock-up is filled with 3-ft long steel rods. Maintain this gain-setting throughout the test. Reset the LMA signal to its reference level by pushing the LMA reset button. Read the voltage on the meter connected to the LMA Output Jack. Now fill the mock-up assembly symmetrically by placing into each adjacent 5/8 in. diameter peripheral tube one 5/32 in. (0.156 in. diameter) rod, and finally one into the central tube. Then, in the same manner, place a second rod into each tube, etc., until all seven 5/8 in. tubes contain seven such rods. Observe, and record, the output voltage reading each time a rod is added to the assembly.

Test #7

Repeat test #6, except that: (a) the large mock-up assembly is now loaded with, altogether 77, 1/8 in. rods (instead of with 49-$\frac{5}{32}$ in. ones), and (b) the voltage changes are only recorded each time two rods have been added, symmetrically, to each 5/8 in. diameter tube (instead of per rod change).

Test #8

Completely fill each of the large mock-up assembly's seven 5/8 in. tubes with 11-$\frac{1}{8}$ in. (0.126 in. diameter) rods. Insert this assembly into the open sensor-head, and then close the latter. Adjust the instrument's LMA Gain Potentiometer dial-setting as appropriate for the amount of metal initially inside the sensor-head, in line with the manufacturer's relevant instructions (e.g., see Table 2 of ref. 26), i.e., in this case to 1.32 for a total metallic cross-sectional area of 0.96 in^2. Maintain this setting throughout the test. Push the LMA reset button. Remove, consecutively, two 1/8 in. rods from each of the six peripheral tubes, and finally from the central one. Continue in this manner, by removing two rods from each peripheral tube, etc., until all rods have been removed. Observe, and record, the voltage changes each time two rods have been removed.

B.) Tests not involving the mock-up assemblies — tests #9 through #11

Test #9a

Do not use a mock-up assembly. Instead, use 'thicker' and 'thinner', 3-ft long, steel rods. A 'test-set' consists of one thicker and one thinner rod, with the metallic cross-sectional area of the thinner one representing a known amount (some 2.3% to 10.0%) of the thicker one's area. Insert a 'test-set' of one thick and one thin rod (exceptionally only the $\frac{1}{16}$ in. one) into the closed sensor-head. Adjust the instrument's LMA Gain Potentiometer dial-setting to a reading of 10. Maintain this setting throughout the test. Push the LMA reset button. Remove the thinner of the two rods from the closed sensor-head. Observe, and record, the resulting voltage changes on both a Volt-meter and on the instrument's strip-chart recorder. Repeat the foregoing procedure with all available 'test sets'.

The following nominal rod sizes (in inches) were used to make up the individual 'test-sets': $\frac{1}{16}$ (on its own); $\frac{23}{64}$ with $\frac{7}{64}$; $\frac{27}{64}$ with $\frac{9}{64}$; $\frac{37}{64}$ with $\frac{3}{16}$; $\frac{23}{32}$ with $\frac{7}{32}$; $\frac{13}{16}$ with $\frac{17}{64}$; $\frac{13}{16}$ with $\frac{7}{32}$; 1.0 with $\frac{21}{64}$; 1.0 with $\frac{7}{32}$; $1\frac{5}{64}$ with $\frac{21}{64}$; $1\frac{5}{64}$ with $\frac{7}{32}$; $1\frac{7}{16}$ with $\frac{29}{64}$; and , $1\frac{7}{16}$ with $\frac{7}{32}$.

Test #9b

Do not use a mock-up assembly. A basic 'test-set' now consists of from two (as in test #9a) to seven 3-ft long steel rods. The total metallic cross-sectional areas of these 'test-sets' approximate those of a range of wire-ropes. Specifically (all dimensions are in inches):

— the $\frac{5}{32}$ plus $\frac{1}{16}$ rods simulate a $\frac{1}{4}$ in., 8×19, S, FC, rope;

— the $\frac{37}{64}$ plus $\frac{3}{16}$ rods simulate a $\frac{3}{4}$ in., *Constructex* rope;

— the $\frac{23}{64}$ plus $\frac{7}{32}$ rods simulate a 1.0 in., 6×19, IWRC rope;

— the $\frac{13}{16}$ plus $\frac{17}{64}$ rods simulate a $1\frac{1}{8}$ in., 6×27, FS, FC, rope;

— the 1.0 plus $\frac{21}{64}$ rods simulate a $1\frac{1}{4}$ in., 19×19, *Dyform*, rot. resist. rope;

— the $1\frac{5}{64}$ plus $\frac{21}{64}$ rods simulate a $1\frac{1}{2}$ in., 6×19, IWRC, rope;

— the $1\frac{7}{16}$ plus $\frac{29}{64}$ rods simulate a 2.0 in., 6×27, FS, FC (or a $2\frac{1}{4}$ in., 8×19, S, FC) rope;

— the $1\frac{7}{16}$ plus $\frac{29}{64}$ plus $\frac{37}{64}$ rods simulate a $2\frac{1}{8}$ in., 19×7, rot. resist. rope;

— the $1\frac{7}{16}$ plus $\frac{29}{64}$ plus $\frac{13}{16}$ plus $\frac{37}{64}$ rods simulate a $2\frac{1}{4}$ in., 6×27, FS, IWRC, rope;

— the $1\frac{7}{16}$ plus $\frac{29}{64}$ plus 1.0 plus $\frac{23}{32}$ rods simulate a $2\frac{3}{8}$ in., *Constructex* rope;

— the $1\frac{7}{16}$ plus $\frac{29}{64}$ plus $\frac{13}{16}$ plus $\frac{37}{64}$ plus $\frac{27}{64}$ plus $\frac{21}{64}$ plus $\frac{23}{32}$ rods simulate a $2\frac{1}{2}$ in., FS, IWRC rope.

Insert one of these basic 'test-sets' into the sensor-head. Adjust the LMA Gain Potentiometer dial-setting as appropriate for the amount of metal initially inside the sensor-head, in line with the manufacturer's relevant tabulation. Maintain this setting throughout the test. Push the LMA reset button. Remove the thinnest rod of the set from the sensor-head. Observe, and record, the resulting induced voltage on both the attached Volt-meter, and on the strip-chart recorder.

Test #9c

Use the same basic 'test-sets' as in test #9b. However: (a) add one additional 'thin' rod to each set, and (b) set to, and maintain throughout each test-series, the LMA Gain Potentiometer dial at an arbitrary value. As an example: (a) we so added, to the basic 'test-sets' of test #9b, once a $\frac{1}{16}$ in., and once a $\frac{23}{64}$ in. steel rod, and (b) we used a continuous potentiometer dial-setting of 10.

Insert one of the basic 'test-sets' into the sensor-head. Set the LMA Gain Potentiometer dial. Push the LMA reset button. Remove only the additional 'thin' rod from the head, and then reinsert it. Observe, and record, the resulting induced voltage on both the attached Volt-meter, and on the strip-chart recorder.

Test #9d

Proceed as in case of test #9c, except that in this case : (a) we once added a $\frac{1}{16}$ in., and once a $\frac{21}{64}$ in. rod to the basic 'test-sets' of test #9b, (b) we used a continuous LMA Gain setting of 1 (instead of 10), and (c) we used a few additional, slightly different, basic 'test-sets' as well. The basic 'test-sets' now consisted of (all dimensions are in inches):

- $\frac{37}{64}$ plus $\frac{3}{16}$ rods;
- $\frac{23}{32}$ plus $\frac{7}{32}$ rods;
- $\frac{13}{16}$ plus $\frac{17}{64}$ rods;
- 1.0 plus $\frac{21}{64}$ rods;
- a 1.0 in. rod;
- $1\frac{5}{64}$ plus $\frac{21}{64}$ rods;
- $1\frac{7}{16}$ plus $\frac{29}{64}$ rods;
- $1\frac{7}{16}$ plus $\frac{37}{64}$ plus $\frac{29}{64}$ in. rods;
- $1\frac{7}{16}$ plus $\frac{13}{16}$ plus $\frac{37}{64}$ plus $\frac{29}{64}$ in. rods;

— $1\frac{7}{16}$ plus 1.0 plus $\frac{23}{32}$ plus $\frac{29}{64}$ in. rods;

— $1\frac{7}{16}$ plus $\frac{13}{16}$ plus $\frac{37}{64}$ plus $\frac{29}{64}$ plus $\frac{27}{64}$ plus $\frac{23}{64}$ plus $\frac{21}{64}$ in. rods.

Test #9e

Proceed as in case of test #9b, except that after first removing the thinnest rod of the basic 'test-set' inside the sensor-head, continue to remove, one at a time, all the other rods of the set as well. Once the head is empty, push the LMA reset reset button. Then reinsert, one at a time, all the rods, in the same order as they were removed. The basic 'test-sets' now consisted of (all dimensions are in inches):

— $\frac{37}{64}$ plus $\frac{3}{16}$ rods;

— $\frac{23}{32}$ plus $\frac{7}{32}$ rods;

— $\frac{13}{16}$ plus $\frac{17}{64}$ rods;

— 1.0 plus $\frac{21}{64}$ rods;

— $1\frac{5}{64}$ plus $\frac{21}{64}$ rods;

— $1\frac{7}{16}$ plus $\frac{29}{64}$ rods;

— $1\frac{7}{16}$ plus $\frac{37}{64}$ plus $\frac{29}{64}$ in. rods;

— $1\frac{7}{16}$ plus $\frac{13}{16}$ plus $\frac{37}{64}$ plus $\frac{29}{64}$ in. rods;

— $1\frac{7}{16}$ plus 1.0 plus $\frac{23}{32}$ plus $\frac{29}{64}$ in. rods;

— $1\frac{7}{16}$ plus $\frac{13}{16}$ plus $\frac{23}{32}$ plus $\frac{37}{64}$ plus $\frac{29}{64}$ plus $\frac{27}{64}$ plus $\frac{21}{64}$ in. rods.

Observe, and record on both a Volt-meter and on the instrument's strip-chart recorder, the resulting voltage changes as each rod is removed/reinserted.

Test #9f

Repeat test #9e, except that removal of the rods from the sensor-head, and their subsequent reinsertion, now commences with the thickest (rather than with the thinnest) rod.

Test #9g

Use only those basic 'test-sets', of the ones previously enumerated for performing test #9b, that had been used there for simulating rope sizes 2.0 in. through $2\frac{1}{2}$ in. Insert these, one complete set at a time, into the sensor-head. Adjust the LMA Gain Potentiometer dial-setting as appropriate for the metal initially inside the sensor-head, either: (1) in line with the manufacturer's relevant tabulation, or, (2) if available, as obtained individually (e.g., as per test #10b). Maintain this setting throughout the test series. Push the LMA reset button. Observe, and record, the induced voltage as each rod is removed/reinserted during the following test process (all dimensions are in inches):

2 in. assembly; Gain-setting of 1.67

— remove, and reinsert, the $\frac{29}{64}$ in. rod (ten times, so as to check 'repeatability').

$2\frac{1}{8}$ in. assembly; Gain-setting of 1.57

— remove, and reinsert, the $\frac{37}{64}$ in. rod (repeat ten times);

— remove, and reinsert, the $\frac{29}{64}$ in. rod (repeat ten times);

— remove first the $\frac{37}{64}$ in., and then the $\frac{29}{64}$ in. rod; then reinsert them, one at a time, in the reverse order (repeat ten times);

— remove first the $\frac{29}{64}$ in., and then the $\frac{37}{64}$ in. rod; then reinsert them, one at a time, in the reverse order (repeat ten times).

$2\frac{1}{4}$ in. assembly; Gain-setting of 1.46

— remove, and reinsert, the $\frac{37}{64}$ in. rod (repeat ten times);

— remove, and reinsert, the $\frac{29}{64}$ in. rod (repeat ten times);

— remove, and reinsert, the $\frac{13}{16}$ in. rod (repeat ten times);

— remove first the $\frac{37}{64}$ in., and then the $\frac{29}{64}$ in. rod; then reinsert them, one at a time, in the reverse order (repeat ten times);

— remove first the $\frac{29}{64}$ in., and then the $\frac{37}{64}$ in. rod; then reinsert them, one at a time, in the reverse order (repeat ten times);

— remove first the $\frac{13}{16}$ in., then the $\frac{37}{64}$ in., and then the $\frac{29}{64}$ in. rod; then reinsert them, one at a time, in the reverse order (repeat ten times);

— remove first the $\frac{29}{64}$ in., then the $\frac{37}{64}$ in., and then the $\frac{13}{16}$ in. rod; then reinsert them, one at a time, in the reverse order (repeat ten times).

2$\frac{3}{8}$ in. assembly; Gain-setting of 1.47

Perform the same rod removal/reinsertion routine with the 'test-sets' of this size assembly, as has been previously described for the 2.0 in. through 2$\frac{1}{4}$ in. assemblies.

2$\frac{1}{2}$ in. assembly; Gain-setting of 1.48

Perform the same rod removal/reinsertion routine with the 'test-sets' of this size assembly, as has been previously described for the 2.0 in. through 2$\frac{3}{8}$ in. assemblies.

Test #9h

Repeat test #9e, except that now slightly different 'test-sets' are to be used, with a slightly different rod removal/reinsertion sequence. Also, now the LMA Gain Potentiometer dial setting is always 1 (rather than a variable setting, depending on the initial amount of metal in the sensor-head). Specifically, the procedure now consists of the following:

Adjust the LMA Gain Potentiometer dial-setting to 1. Push the LMA reset button. Add a 1$\frac{7}{16}$ in. rod to the empty sensor-head. Reset the LMA. Add a $\frac{29}{64}$ in. rod. Reset the LMA. Add, one at a time and in the given order, a 1$\frac{5}{64}$ in.; a $\frac{37}{64}$ in.; a $\frac{23}{64}$ in.; and a $\frac{21}{64}$ in. rod. Now remove, one at a time and in the given order, the 1$\frac{7}{16}$ in.; $\frac{29}{64}$ in.; 1$\frac{5}{64}$ in.; $\frac{21}{64}$ in.; $\frac{23}{64}$ in.; and $\frac{37}{64}$ in. rods.

Observe, and record, the resulting voltage changes as each rod is removed/reinserted, on both a Volt-meter and on the instrument's strip-chart recorder.

Test #10a

Set to, and maintain throughout the test-series, the LMA Gain Potentiometer dial at an arbitrary value, low enough to ensure that throughout the test the induced voltages do not exceed the saturation level of the output-amplifier. In our tests we chose a dial setting of 1 for rod diameters $\frac{1}{16}$ in. through 1.0 in., and 0.5 for diameters in excess of 1.0 in.

Push the LMA reset button. Insert, one only at a time, into the empty sensor-head, and then remove, each of the 3-ft long steel rods used in tests #9a through #9d, i.e., rod sizes (in inches): $\frac{1}{16}$; $\frac{7}{64}$; $\frac{9}{64}$; $\frac{3}{16}$; $\frac{7}{32}$; $\frac{17}{64}$; $\frac{21}{64}$; $\frac{23}{64}$; $\frac{27}{64}$; $\frac{29}{64}$; $\frac{37}{64}$; $\frac{23}{32}$; $\frac{13}{16}$; 1.0; $1\frac{5}{64}$; and, $1\frac{7}{16}$.

Repeat the insertion/removal process of each rod size ten times. Observe, and record, the resulting voltage changes on both a Volt-meter and on the instrument's strip-chart recorder.

Test #10b

Proceed as in case of test #9b, except that rather than using the manufacturer's tabulation alone, the LMA Gain Potentiometer dial is now adjusted to a range of values, until the recorded %LMA chart-reading — while only the thinnest rod of the set is removed — exactly matches the 'true' %LMA value as established by calculation (the cross-sectional areas of the test-rods are known, exactly). Observe, and record, the resulting voltage changes on both a Volt-meter and on the instrument's strip-chart recorder, noting that an induced voltage of 100 mV is to be equal to a loss-of-metallic-area of 1.0%.

Test #10c

Set the LMA Gain Potentiometer dial to 1. Push the LMA reset button. Insert into the empty sensor-head, in 10 seperate stages, all rods used during test #9b and #9d, one at a time. Push the LMA reset button each time saturation level of the output amplifier is exceeded, or even approached.

Specifically (all dimensions are in inches) proceed as follows:

(1) LMA reset; add the $\frac{37}{64}$ rod; add the $\frac{21}{64}$ rod; remove the $\frac{21}{64}$ rod; remove the $\frac{37}{64}$ rod.

(2) LMA reset; add the $\frac{27}{64}$ rod; add the $\frac{29}{64}$ rod; add the $\frac{7}{32}$ rod; LMA reset; add the $\frac{37}{64}$ rod; add the $\frac{21}{64}$ rod; remove the $\frac{21}{64}$ rod; remove the $\frac{37}{64}$ rod; LMA reset; remove the $\frac{7}{32}$ rod; remove the $\frac{29}{64}$ rod; remove the $\frac{27}{64}$ rod.

(3) LMA reset; add the 1.0 in. rod; LMA reset; add the $\frac{37}{64}$ rod; add the $\frac{21}{64}$ rod; remove the $\frac{21}{64}$ rod; remove the $\frac{37}{64}$ rod; LMA reset; remove the 1.0 in. rod.

(4) LMA reset; add the $1\frac{5}{64}$ rod; LMA reset; add the $\frac{37}{64}$ rod; add the $\frac{21}{64}$ rod; remove the $\frac{21}{64}$ rod; remove the $\frac{37}{64}$ rod; LMA reset; remove the $1\frac{5}{64}$ rod.

(5) LMA reset; add the $1\frac{5}{64}$ rod; LMA reset; add the $\frac{23}{32}$ rod; LMA reset; add the $\frac{37}{64}$ rod; add the $\frac{21}{64}$ rod; remove the $\frac{21}{64}$ rod; remove the $\frac{37}{64}$ rod; LMA reset; remove the $\frac{23}{32}$ rod; LMA reset; remove the $1\frac{5}{64}$ rod.

(6) LMA reset; add the $1\frac{7}{16}$ rod; LMA reset; add the $\frac{37}{64}$ rod; add the $\frac{21}{64}$ rod; remove the $\frac{21}{64}$ rod; remove the $\frac{37}{64}$ rod; LMA reset; remove the $1\frac{7}{16}$ rod.

(7) LMA reset; add the $1\frac{7}{16}$ rod; LMA reset; add the $\frac{37}{64}$ rod; LMA reset; add the $\frac{29}{64}$ rod; add the $\frac{23}{64}$ rod; add the $\frac{21}{64}$ rod; remove the $\frac{21}{64}$ rod; remove the $\frac{23}{64}$; remove the $\frac{29}{64}$ rod; LMA reset; remove the $\frac{37}{64}$ rod; LMA reset; remove the $1\frac{7}{16}$ rod.

(8) LMA reset; add the $1\frac{7}{16}$ rod; LMA reset; add the $\frac{13}{16}$ rod; LMA reset; add the $\frac{37}{64}$ rod; add the $\frac{21}{64}$ rod; remove the $\frac{21}{64}$ rod; remove the $\frac{37}{64}$ rod; LMA reset; remove the $\frac{13}{16}$; LMA reset; remove the $1\frac{7}{16}$ rod.

(9) LMA reset; add the $1\frac{7}{16}$ rod; LMA reset; add the $1\frac{5}{64}$ rod; LMA reset; add the $\frac{37}{64}$ rod; add the $\frac{21}{64}$ rod; remove the $\frac{21}{64}$ rod; remove the $\frac{37}{64}$ rod; LMA reset; remove the $1\frac{5}{64}$; LMA reset; remove the $1\frac{7}{16}$ rod.

(10) LMA reset; add the $1\frac{7}{16}$ rod; LMA reset; add the $1\frac{5}{64}$ rod; LMA reset; add the $\frac{37}{64}$ rod; LMA reset; add the $\frac{29}{64}$ rod; add the $\frac{23}{64}$ rod; add the $\frac{21}{64}$ rod; remove the $\frac{21}{64}$ rod; remove the $\frac{23}{64}$ rod; remove the $\frac{29}{64}$ rod; LMA reset; remove the $\frac{37}{64}$ rod; LMA reset; remove the $1\frac{5}{64}$ rod; LMA reset; remove the $1\frac{7}{16}$ rod.

Observe, and record, the resulting voltage changes on both a Volt-meter and on the instrument's strip-chart recorder, as each rod is added/removed.

Test #11

Do not use a mock-up assembly. Use two 3-ft long steel rods, sized $1\frac{7}{16}$ in. (1.623 in^2) and $\frac{29}{64}$ in. (0.161 in^2) — i.e., the thinner one represents 9.9% of the thicker one's metallic cross-sectional area. Insert the thicker rod into, and close the sensor-head. Adjust the instrument's LMA Gain Potentiometer setting to 0.88, i.e., to the value appropriate — according to the manufacturer's tabulation — to this rod's metallic cross-sectional area of 1.623 in^2. Press the LMA reset button. Connect the instrument to its chart-recorder. Set the latter's sensitivity to 50 mV/mm — i.e., to 0.5% LMA per mm of recorder-pen movement (or 2.5% LMA per major chart divison), because an LMA signal of 100 mV is to be equal to a 1.0%LMA. Insert the thinner rod into the sensor-head, alongside the thicker one. Record the resulting voltage change on the LMA strip-chart, i.e., the percentage increase in the recorded metallic cross-sectional area. Repeat the foregoing process with the LMA Gain Potentiometer settings adjusted, respectively, to readings of 0.5; 0.7; 0.88; 0.93; 0.98; 1.2, and 1.4.

With the Magnograph instrument

C.) Tests involving the mock-up assemblies — tests #12 through #17

Test #12

Use the $1\frac{7}{8}$ in. large mock-up assembly. Insert it, while empty, into the insert 'D' equipped sensor-head, and close the head around it. Adjust the Empty Head (E.H.) Zero dial to bring the LMA meter reading to zero. Lock the E.H. Zero control into this position, and do not readjust it for the duration of the test. Adjust the LMA Gain, arbitrarily, to 186. Maintain this setting throughout the test.

Symmetrically fill the mock-up assembly by placing, consecutively, one 5/32 in. (0.156 in. diameter) steel rod into each adjacent 5/8 in. tube of the six ranged along the periphery of the mock-up assembly. Continue to do so until these peripheral tubes are replete, each with seven rods. Finally, place seven rods into the central tube. Observe, and record, the voltage changes as each rod is added. Also, as a final step, readjust the LMA Zero Potentiometer to show zero on the LMA meter, and record the amount of dial adjustment required to obtain this.

Test #13a

Repeat test #12, except that now the central mock-up tube is to be filled concurrently, and in rotation with, the six peripheral ones, instead of remaining empty until the others are replete.

Test #13b

Repeat Test #12, except that now insert 'B' is to be used instead of insert 'D'.

Test #13c

Repeat Test #12, except that now insert 'C' is to be used instead of insert 'D'.

Test #14

Repeat test #13a, except that now 11-$\frac{1}{8}$ in. (0.126 in. diameter) steel rods are to be used to fill each of the seven 5/8 in. diameter mock-up tubes, instead of seven 5/32 in. ones, as had been used previously.

Test #15a

Repeat test #12, except that now: (a) the small mock-up assembly is to be used instead of the large one, (b) 49-$\frac{3}{32}$ in. steel rods are to be used to fill the mock-up, instead of 49-$\frac{5}{32}$ in. ones, and (c) insert 'B' is to be used, instead of insert 'D'.

Test #15b

Repeat of test #15a, exactly.

Test #16a (as performed by operator 'A')

Use the large mock-up assembly, and completely fill its seven 5/8 in. diameter tubes with 49-$\frac{5}{32}$ in. steel rods. Insert this assembly into the insert 'D' equipped sensor-head, and close the head around it. Adjust the LMA Zero Potentiometer so as to obtain a zero reading on the LMA meter, and record the amount of potentiometer dial adjustment required to accomplish this. Do not readjust this setting for the duration of the test. Adjust the LMA gain to correspond to the aforementioned LMA Zero setting, and to the insert size in use, as per the calibration graph the manufacturer supplies for each Magnograph (see sample in ref. 17, Fig. 3).

Remove, consecutively, one 5/32 in. rod from each adjacent tube of the six peripheral ones, and finally from the central mock-up tube. Reverse the order of the foregoing process, by reinserting one rod at a time into each of the tubes. Observe, and record, the voltage changes each time a rod is removed/replaced.

Test #16b (as performed by operator 'B')

Repeat of test #16a, but only up to the point at which one rod had been removed from each of the 5/8 in. diameter mock-up tubes.

Test #17a (as performed operator 'A')

Repeat of test #16a, except that now: (a) use the small mock-up, instead of the large one, (b) use insert 'C' instead of insert 'D', and (c) fill the mock-up with 49-$\frac{1}{8}$ steel rods (instead of with 49-$\frac{5}{32}$ ones).

Test #17b (as performed by operator 'B')

Repeat of test #17a, except for the use of insert 'B' instead of insert 'C'.

Test #17c (as performed by operator 'B')

Repeat of test #17b, but only up to the point at which one rod had been removed from each of the 3/8 in. diameter mock-up tubes.

D.) Tests not involving the mock-up assemblies — tests #18 and #19

Test #18a

Repeat of test #15, except that instead of inserting more and more 3/32 in. diameter steel rods into the insert 'B' equipped sensor-head, insert an 8-ft length of a 1/2 in., 6×26, IWRC, wire-rope.

Test #18b

Repeat of test #18a, with an 8-ft length of a $1\frac{1}{8}$ in., 6×25, IWRC, wire-rope.

Test #19a

Repeat of test #12, except that instead of inserting more and more 5/32 in. diameter steel rods into the insert 'D' equipped sensor-head, insert an 8-ft length of a 1/2 in., 6×26, IWRC, wire-rope.

Test #19b

Repeat of test #19a, with an 8-ft length of a $1\frac{1}{8}$ in., 6×25, IWRC, wire-rope.

Test #19c

Repeat of test #19a, with an 8-ft length of a $1\frac{1}{2}$ in., 6×25, IWRC, wire-rope.

Test #19d

Repeat of test #19a, with an 8-ft length of a 2.0 in., 6×25, IWRC, wire-rope.

Test #19e

Repeat of test #19a, with an 8-ft length of a $1\frac{7}{16}$ in., FLC, hoist-rope.

APPENDIX 3

Test results

Figures 6 through 33, inclusive

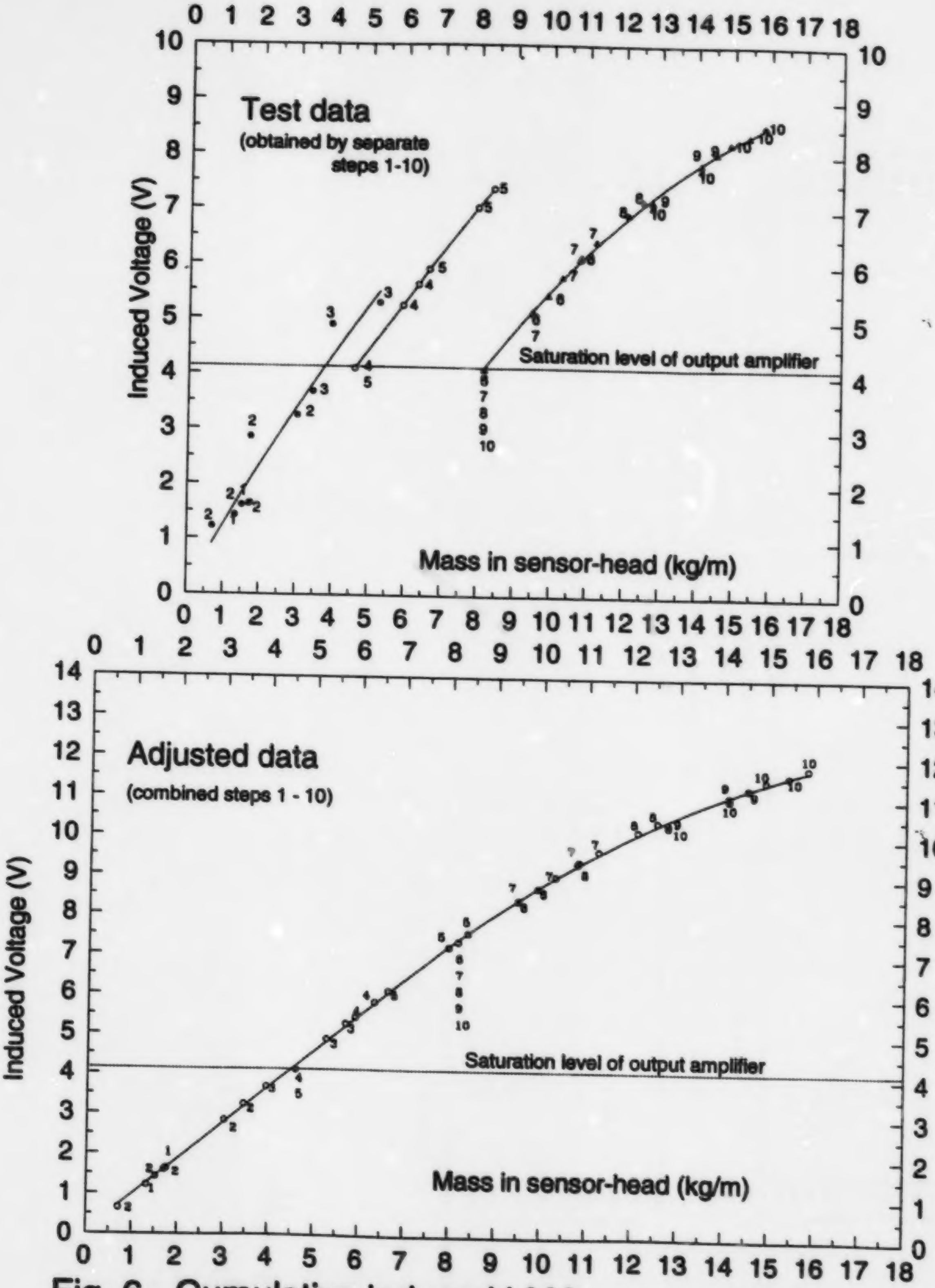


Fig. 6 - Cumulative induced LMA sensor voltages vs mass in sensor-head; LMA-250 instrument (test #10c)

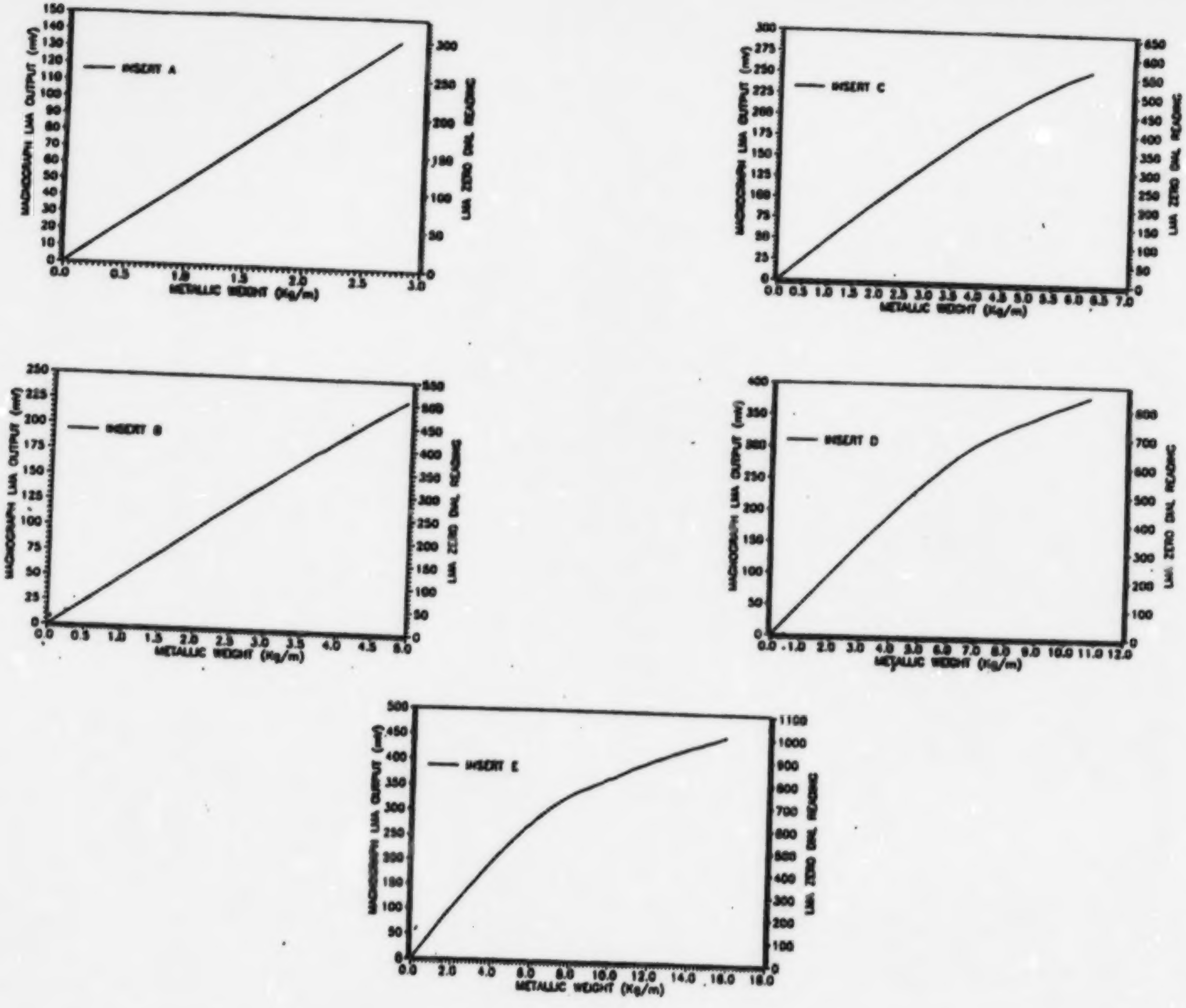


Fig. 7 — Cumulative induced LMA sensor voltage vs mass in sensor-head; MAGNOGRAPH instrument (after ref. 17)

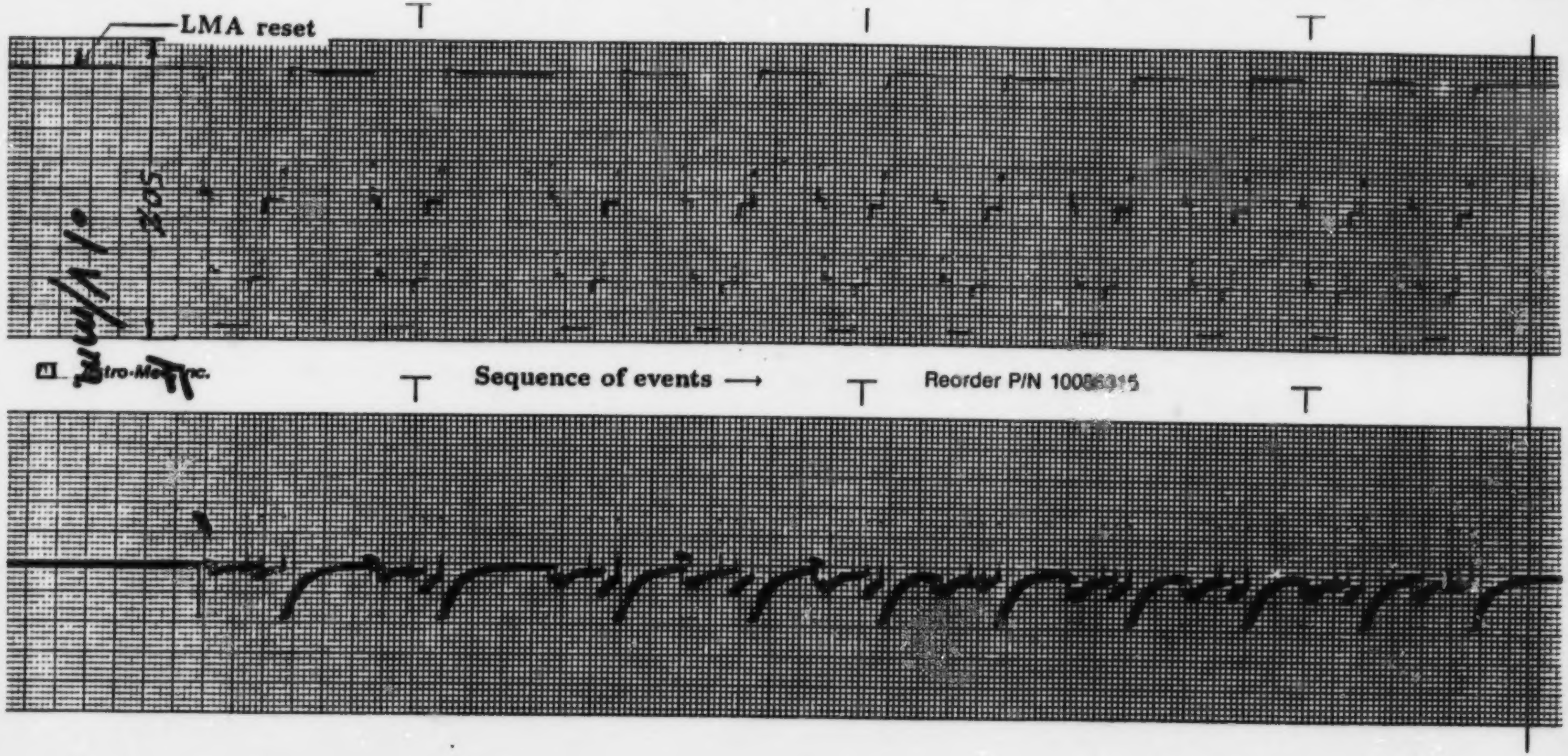


Fig. 8 — Substantial LMA. Inaccurate chart-readings with LMA-250: $2\frac{1}{4}$ in. assembly (12.9 kg/m) in head: Step 'F' (Gain: 1.46; 5% LMA/major chart-division): LMA reset; remove $\frac{13}{16}$ in. + $\frac{37}{64}$ in. + $\frac{29}{64}$ in. rods; reinsert same rods in reverse order (test #9g).

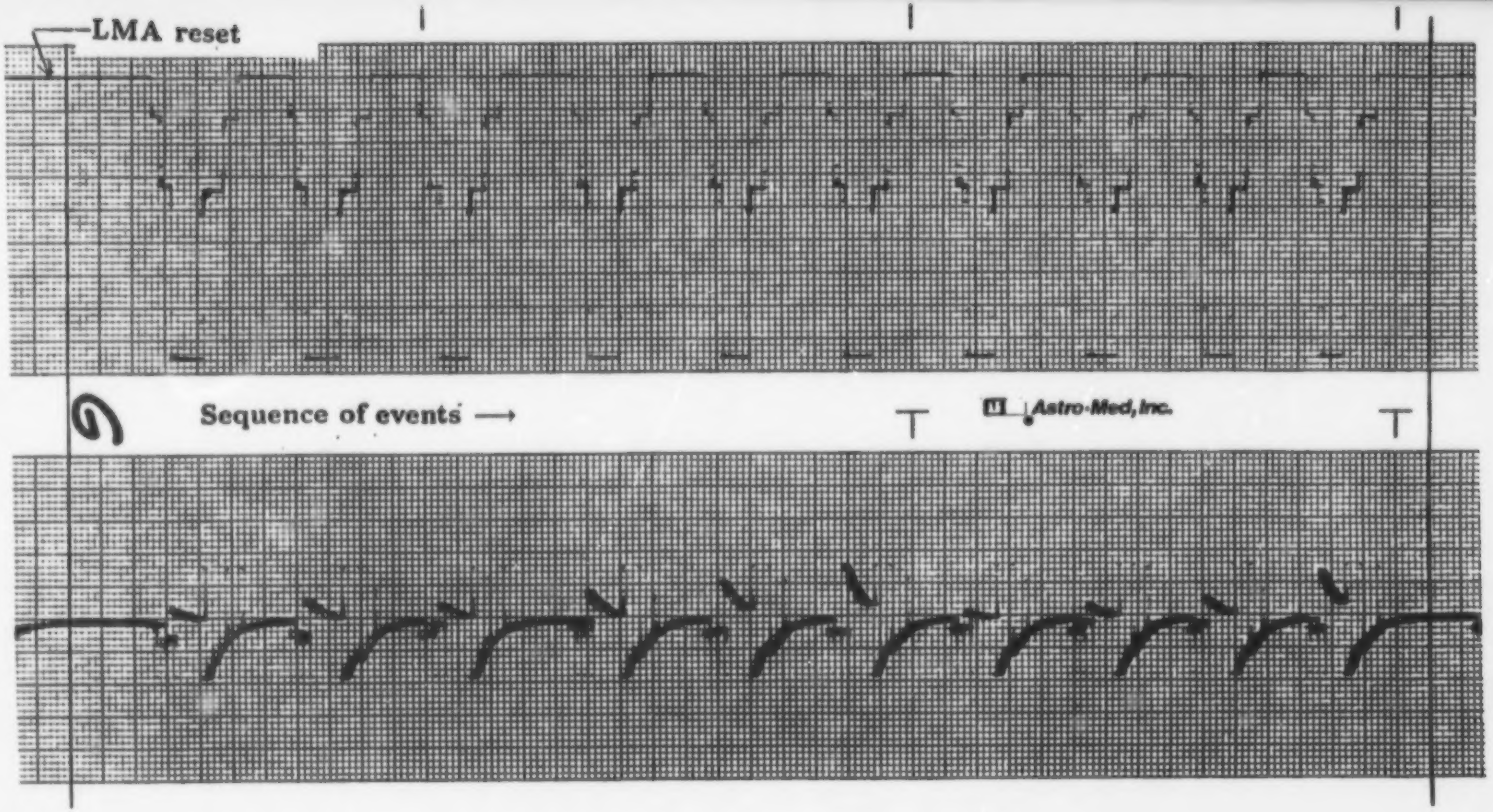


Fig. 9 — Substantial LMA. Inaccurate chart-readings with LMA-250: $2\frac{1}{4}$ in. assembly (12.9 kg/m) in head: Step 'G' (Gain: 1.46; 5% LMA/major chart-division): LMA reset; remove $\frac{29}{16}$ in. + $\frac{37}{64}$ in. + $\frac{13}{16}$ in. rods; reinsert same rods in reverse order (test #9g).

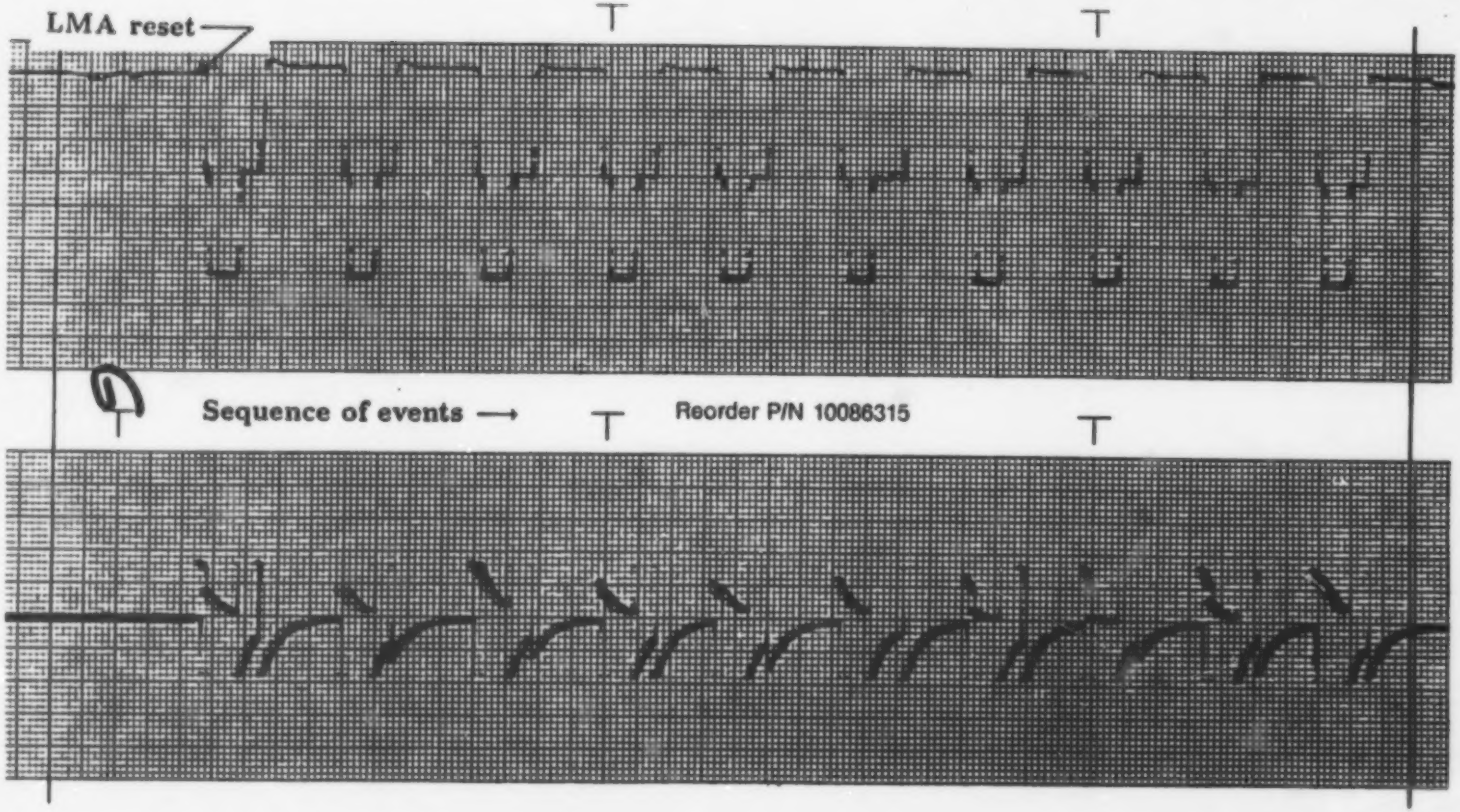


Fig. 10 — Substantial LMA. Inaccurate chart-readings with LMA-250: $2\frac{1}{2}$ in. assembly (16.1 kg/m) in head: Step 'G' (Gain: 1.48; 5% LMA/major chart-division): LMA reset; remove $\frac{13}{16}$ in. + $\frac{23}{32}$ in. rods; reinsert same rods in reverse order (test #9g).

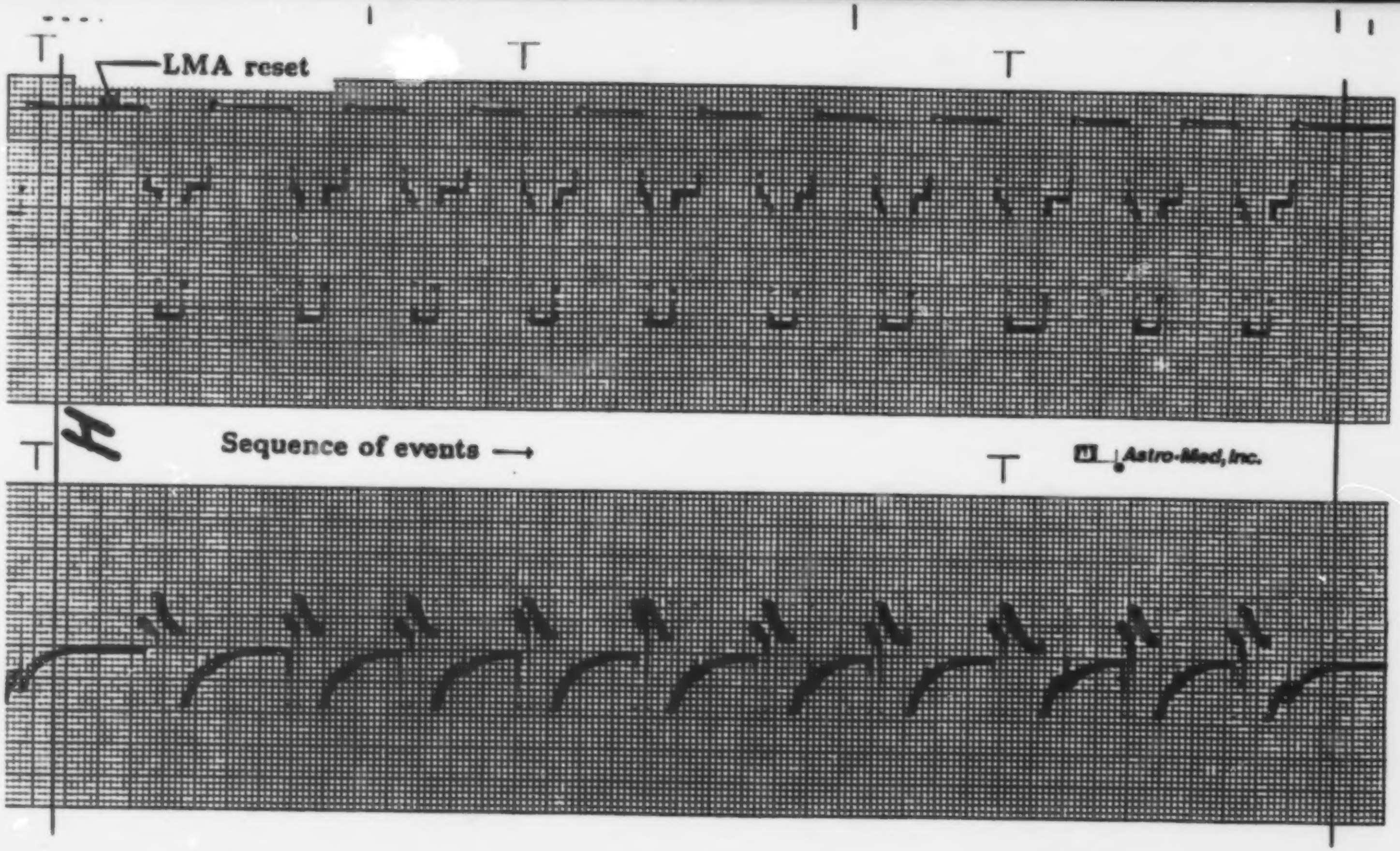


Fig. 11 — Substantial LMA. Inaccurate chart-readings with LMA-250: $2\frac{1}{2}$ in. assembly (16.1 kg/m) in head: Step 'H' (Gain: 1.48; 5% LMA/major chart-division): LMA reset; remove $\frac{23}{32}$ in. + $\frac{13}{16}$ in. rods; reinsert same rods in reverse order (test #9g).

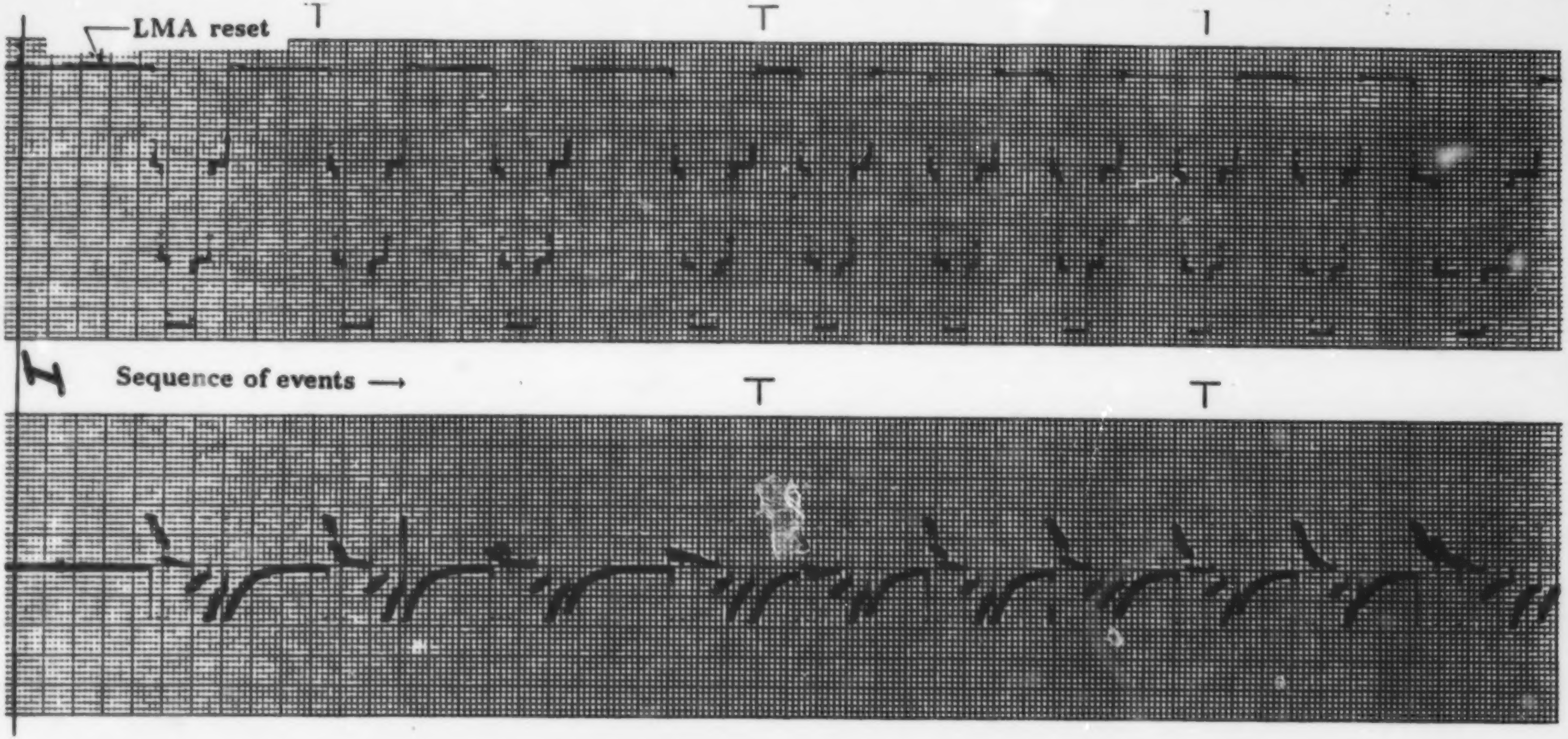


Fig. 12 — Substantial LMA. Inaccurate chart-readings with LMA-250: $2\frac{1}{2}$ in. assembly (16.1 kg/m) in head: Step 'I' (Gain: 1.48; 5% LMA/major chart-division): LMA reset; remove $\frac{13}{16}$ in. + $\frac{23}{32}$ in. + $\frac{37}{64}$ in. rods; reinsert same rods in reverse order (test #9g).

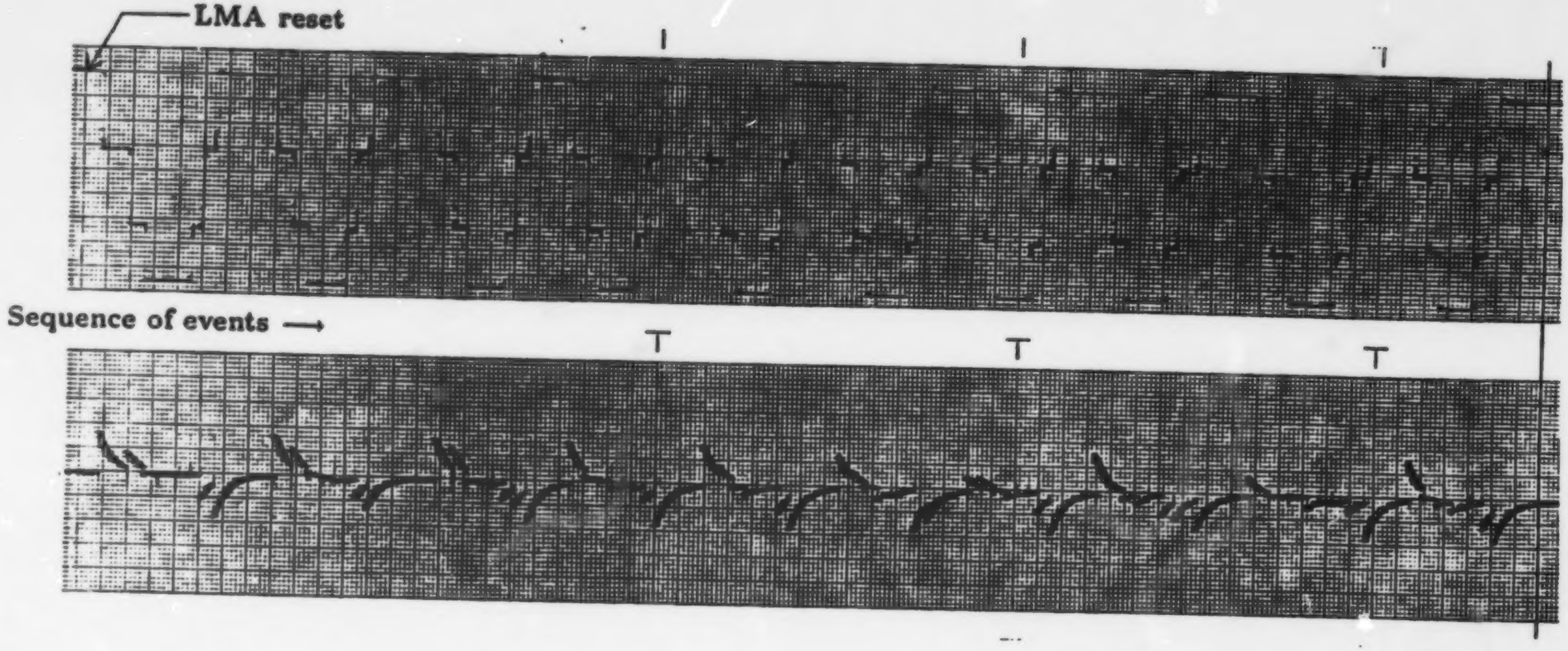


Fig. 13 — Substantial LMA. Inaccurate chart-readings with LMA-250: $2\frac{1}{2}$ in. assembly (16.1 kg/m) in head: Step 'K' (Gain: 1.48; 5% LMA/major chart-division): LMA reset; remove $\frac{13}{16}$ in. + $\frac{23}{32}$ in. + $\frac{37}{64}$ in. + $\frac{29}{64}$ in. rods; reinsert same rods in reverse order (test #9g).

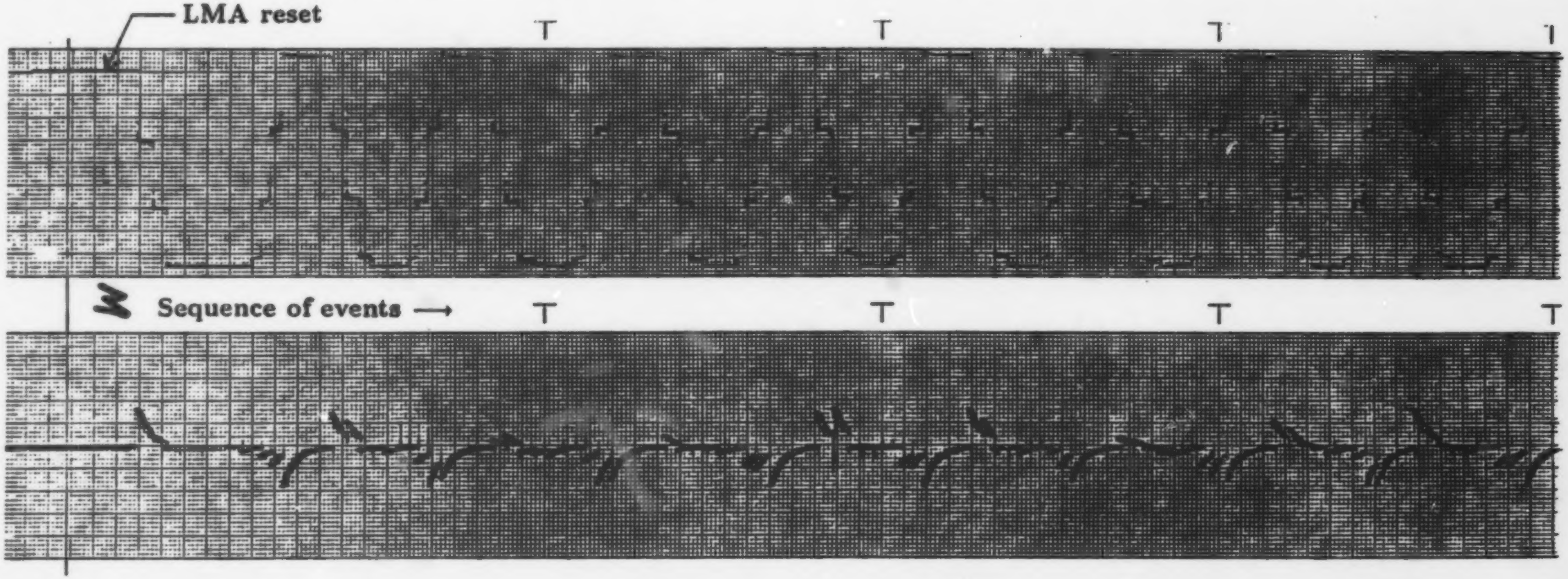


Fig. 14 — Substantial LMA. Inaccurate chart-readings with LMA-250: $2\frac{1}{2}$ in. assembly (16.1 kg/m) in head: Step 'M' (Gain: 1.48; 5% LMA/major chart-division): LMA reset; remove $\frac{13}{16}$ in. + $\frac{23}{32}$ in. + $\frac{37}{64}$ in. + $\frac{29}{64}$ in. + $\frac{27}{64}$ in. rods; reinsert same rods in reverse order (test #9g).

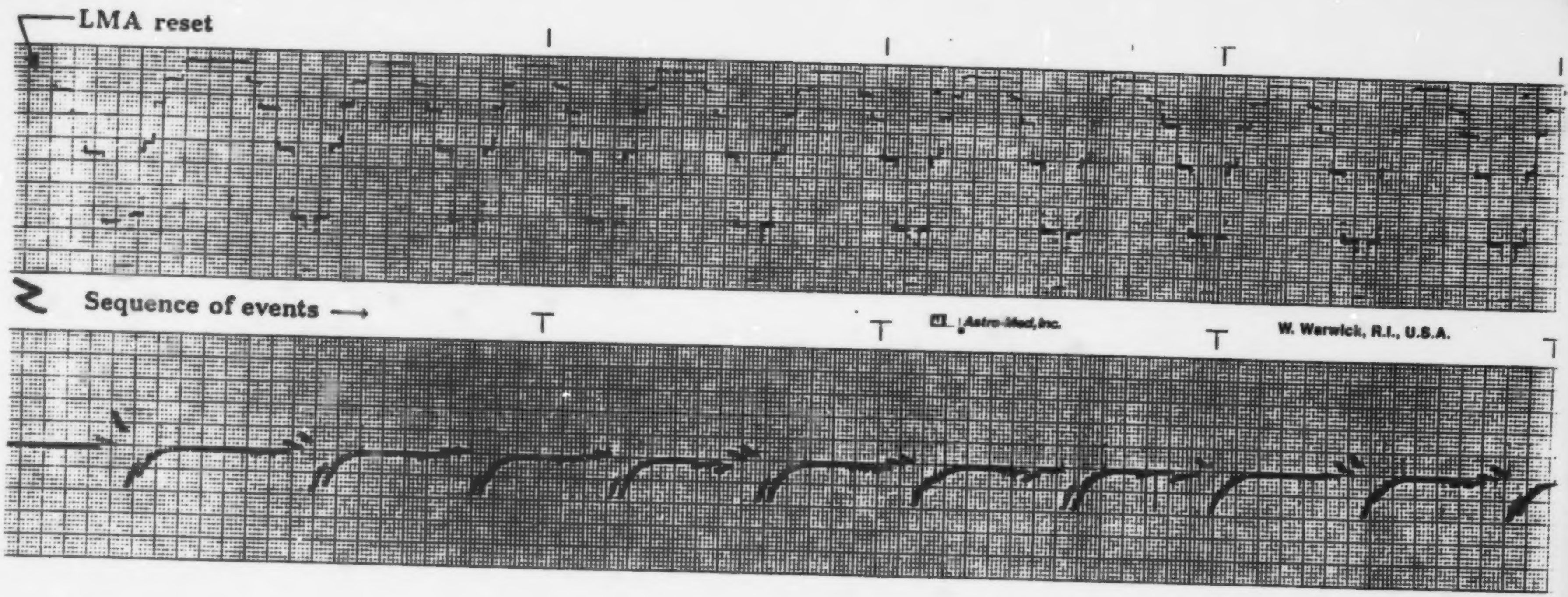


Fig. 15 — Substantial LMA. Inaccurate chart-readings with LMA-250: $2\frac{1}{2}$ in. assembly (16.1 kg/m) in head: Step 'N' (Gain: 1.48; 5% LMA/major chart-division): LMA reset; remove $\frac{27}{64}$ in. + $\frac{29}{64}$ in. + $\frac{37}{64}$ in. + $\frac{23}{32}$ in. + $\frac{13}{16}$ in. rods; reinsert same rods in reverse order (test #9g).

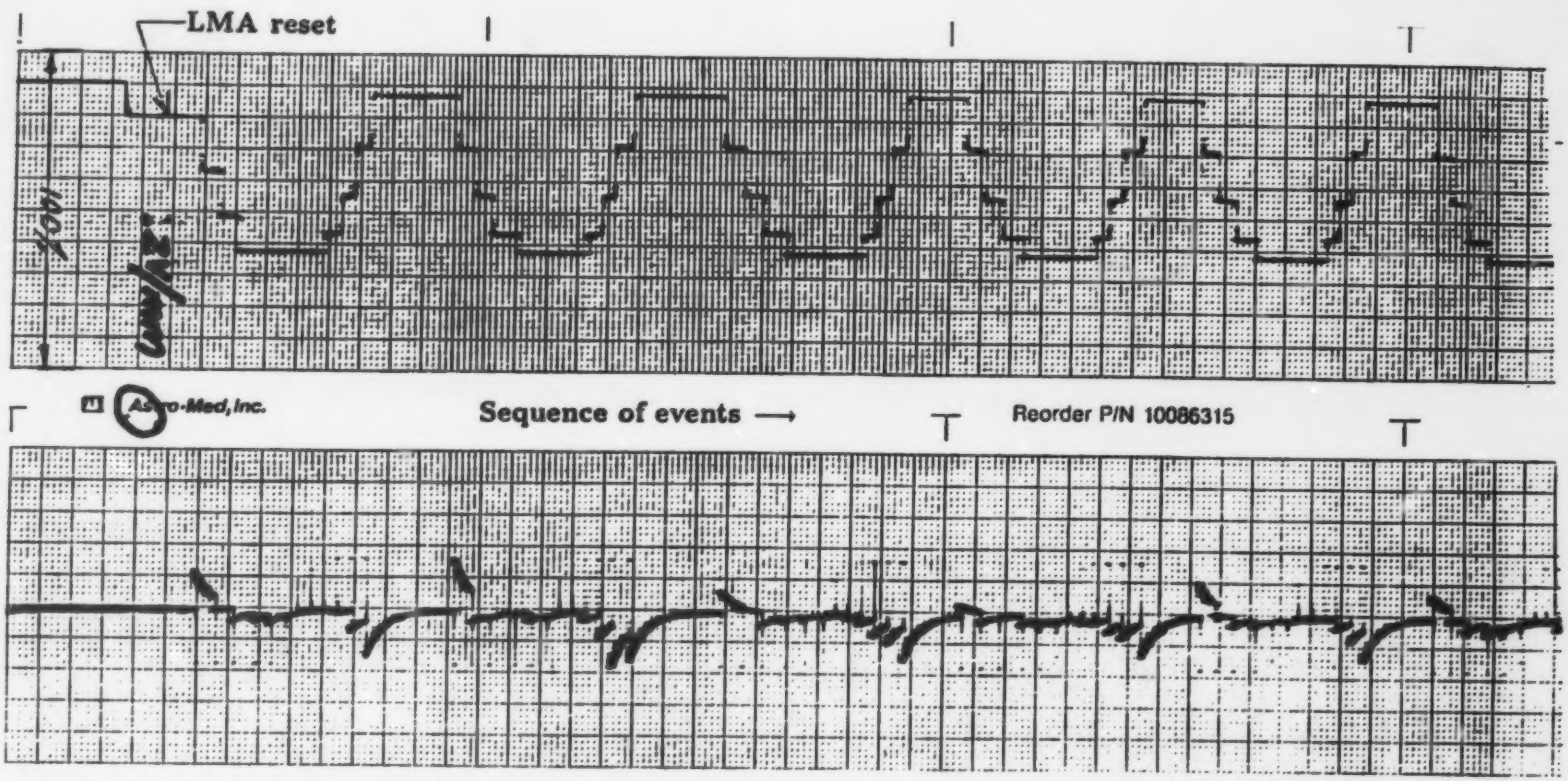


Fig. 16 — Substantial LMA. Inaccurate chart-readings with LMA-250: $2\frac{1}{2}$ in. assembly (16.1 kg/m) in head: Step 'O' (Gain: 1.48; 10% LMA/major chart-division): LMA reset; remove $\frac{13}{16}$ in. + $\frac{23}{32}$ in. + $\frac{37}{64}$ in. + $\frac{29}{64}$ in. + $\frac{27}{64}$ in. + $\frac{21}{64}$ in. rods; reinsert same rods in reverse order (test #9g).

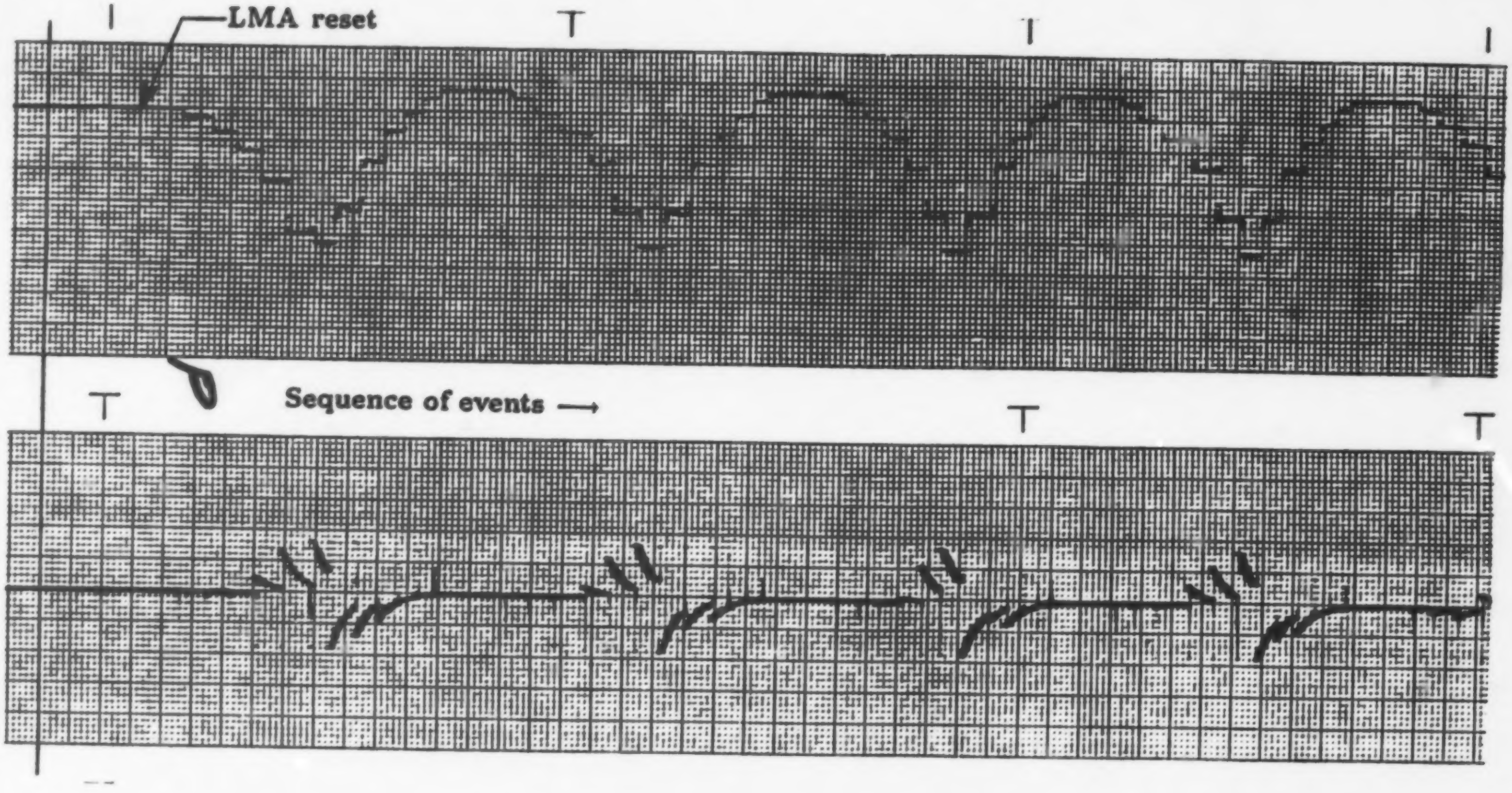


Fig. 17 — Substantial LMA. Inaccurate chart-readings with LMA-250: $2\frac{1}{2}$ in. assembly (16.1 kg/m) in head: Step 'P' (Gain: 1.48; 10% LMA/major chart-division): LMA reset; remove $\frac{21}{64}$ in. + $\frac{27}{64}$ in. + $\frac{29}{64}$ in. + $\frac{37}{64}$ in. + $\frac{23}{32}$ in. + $\frac{13}{16}$ in. rods; reinsert same rods in reverse order (test #9g).

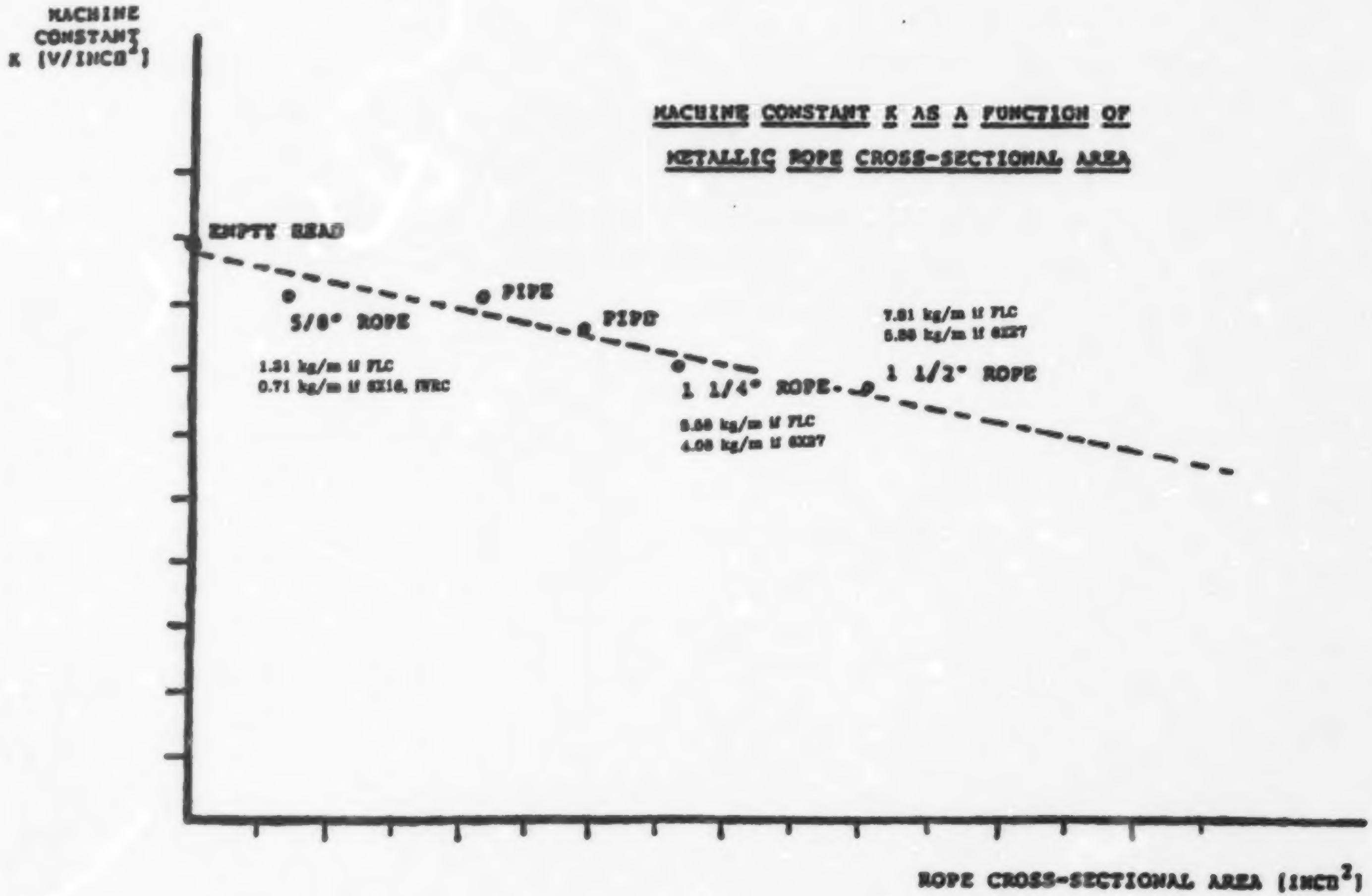


Fig. 18a — Machine Constant, 'K', of LMA-250 instrument (after Appendix 'C' of manufacturer's Operation and Maintenance Manual).

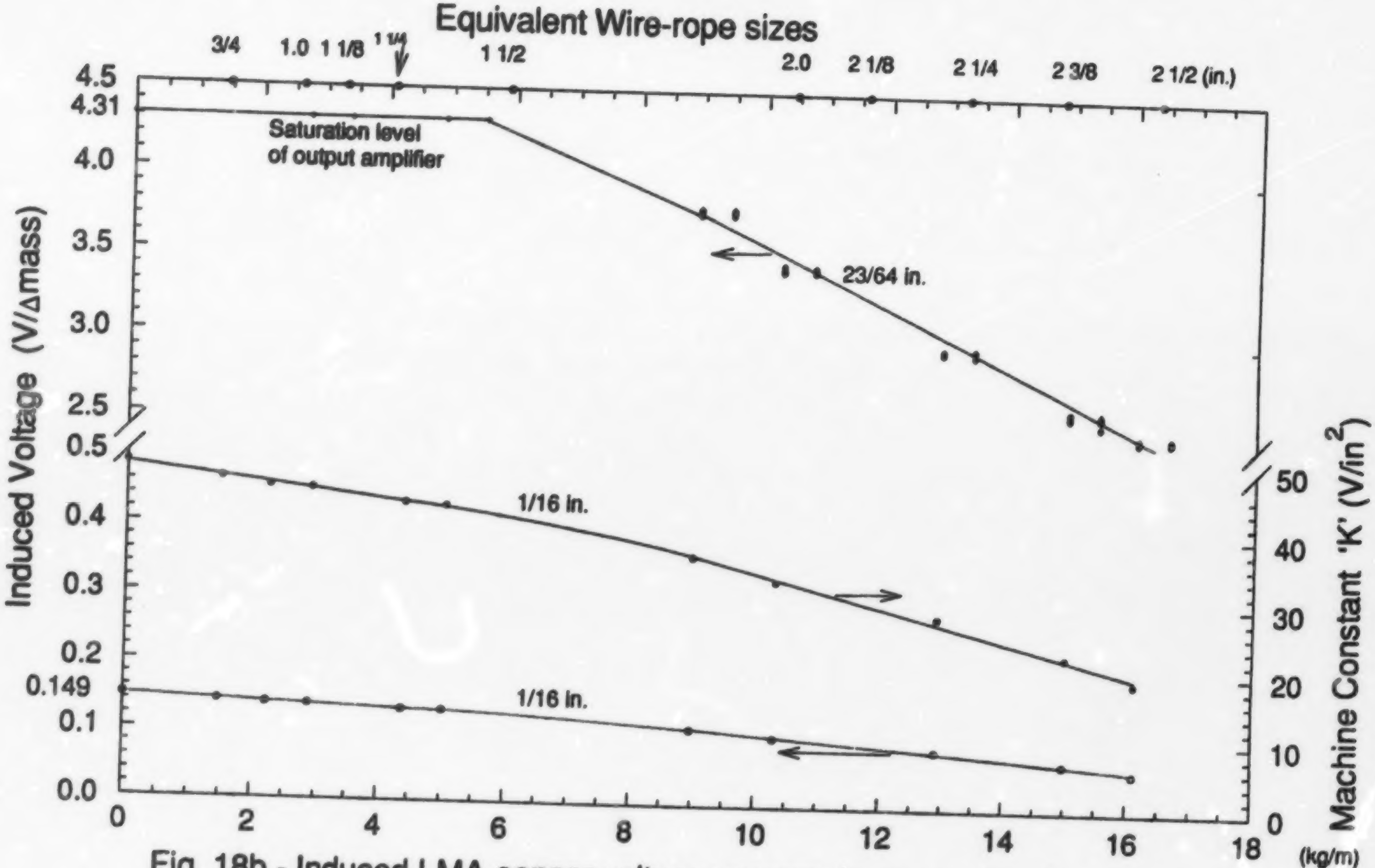


Fig. 18b - Induced LMA-sensor voltage vs mass in sensor-head;
LMA-250 instrument calibration curves with 1/16 in.
and 23/64 in. rods and constant LMA gain setting of 10.0
(test 9c of June 13, and Nov. 14, 1991)

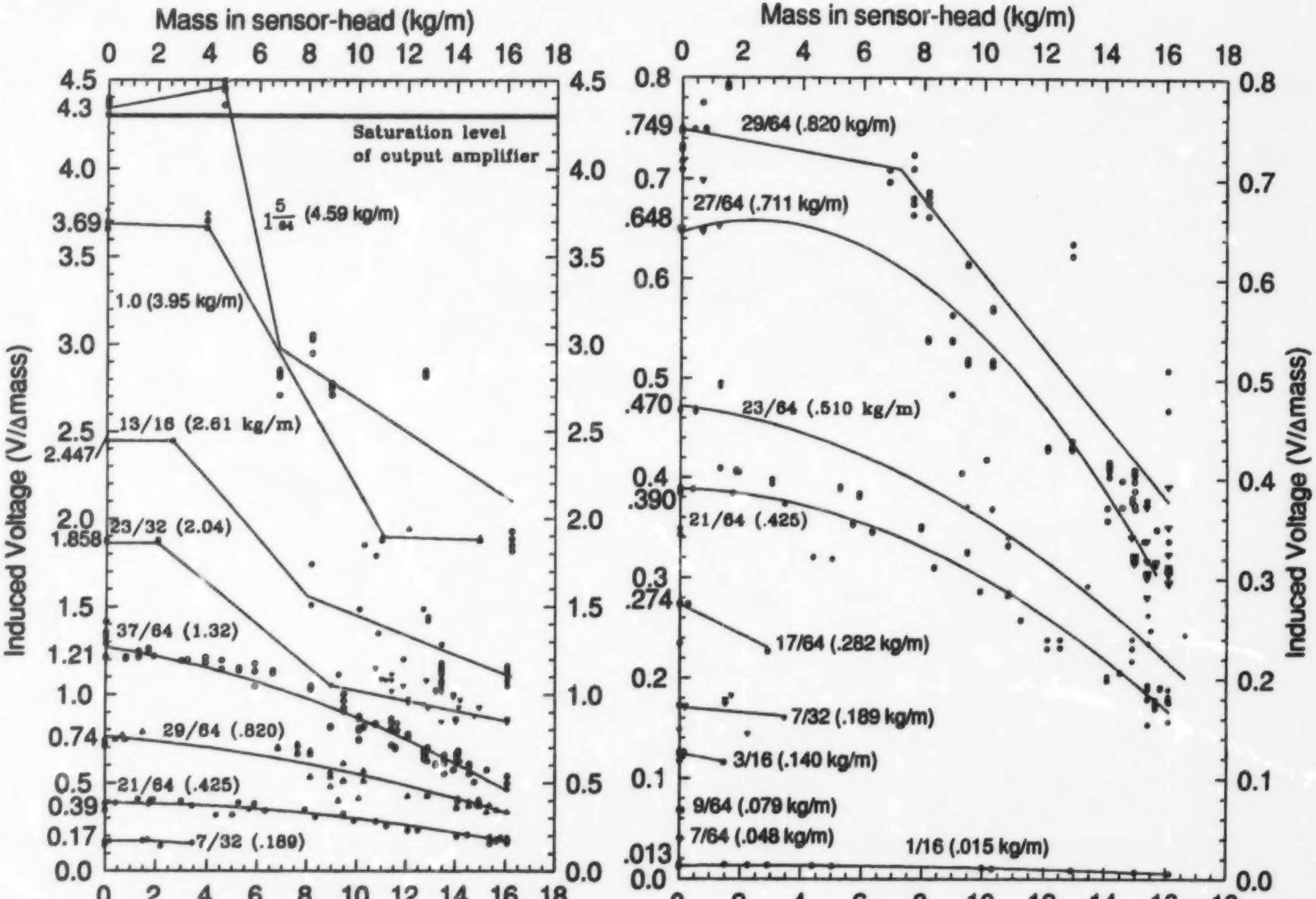


Fig. 19 - Induced voltage per rod insertion/removal vs total mass in sensor-head; LMA-250 instrument calibration curves with constant LMA gain setting of 1.0

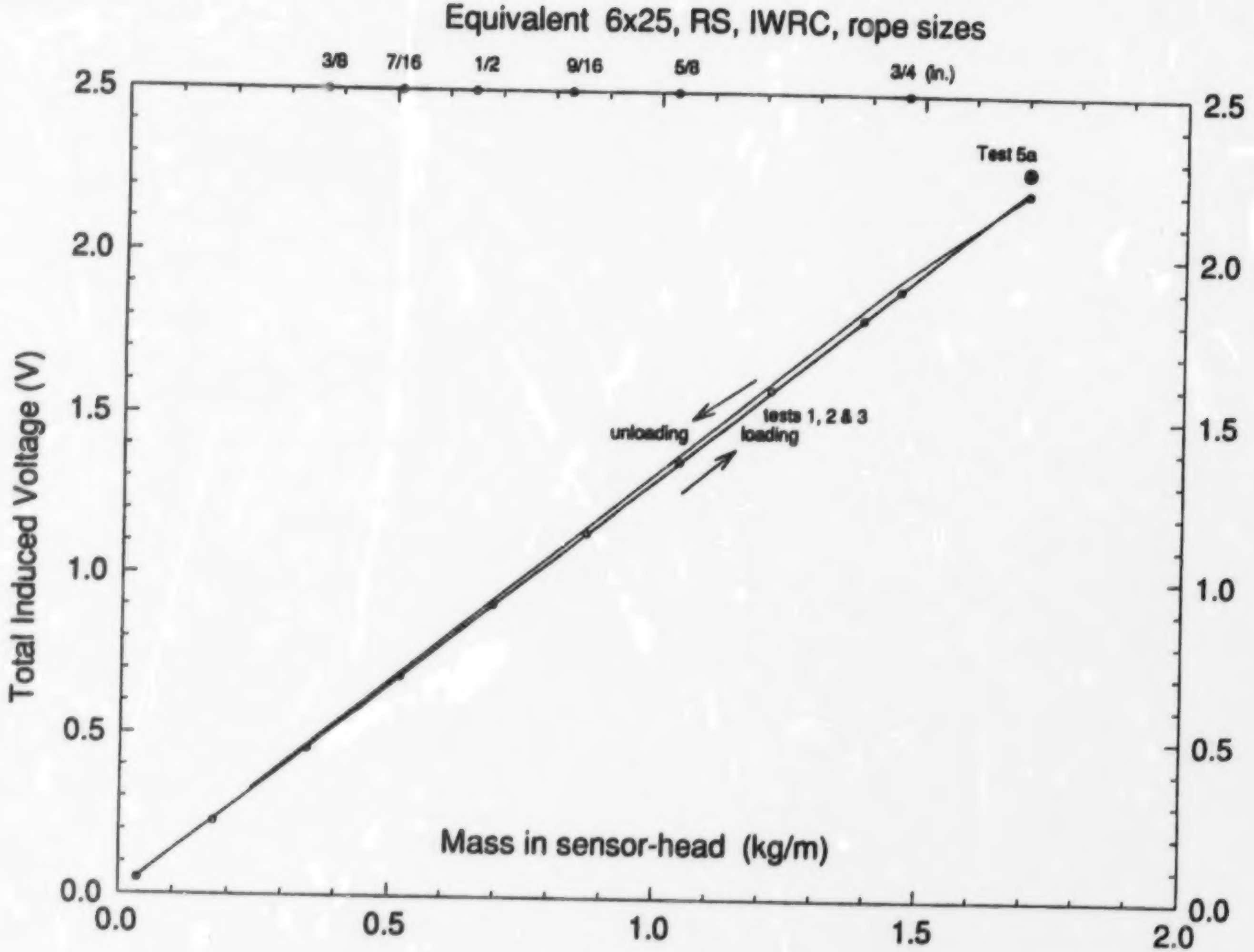
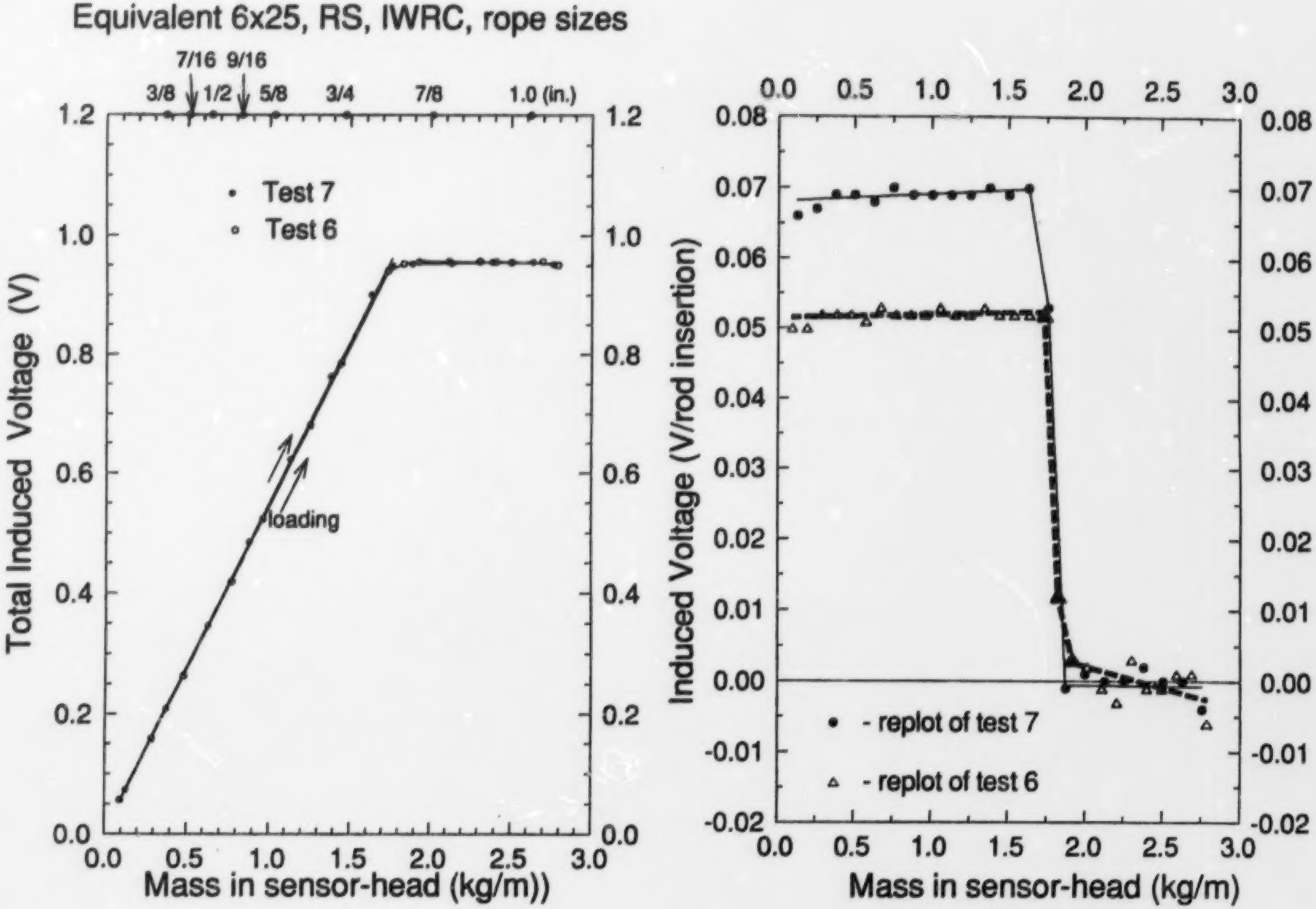


Fig. 20 - Induced LMA-sensor voltage vs cumulative mass in sensor-head; LMA-250 instrument at arbitrary LMA gain of 0.54; small mock-up with 3/32 in. rods. --- Test 1 & 2: symmetric, gradual, loading;

Test 3: non-symmetric, gradual, loading;

Test 5a: entire load inserted as single unit.



(a)

(b)

Fig. 21 - Induced LMA-sensor voltage vs mass in sensor-head (kg/m); LMA-250 instrument at arbitrary LMA gain of 0.20; large mock-up; Symmetric, gradual, loading with 5/32 in. (test 6) or 1/8 in. (test 7) rods.

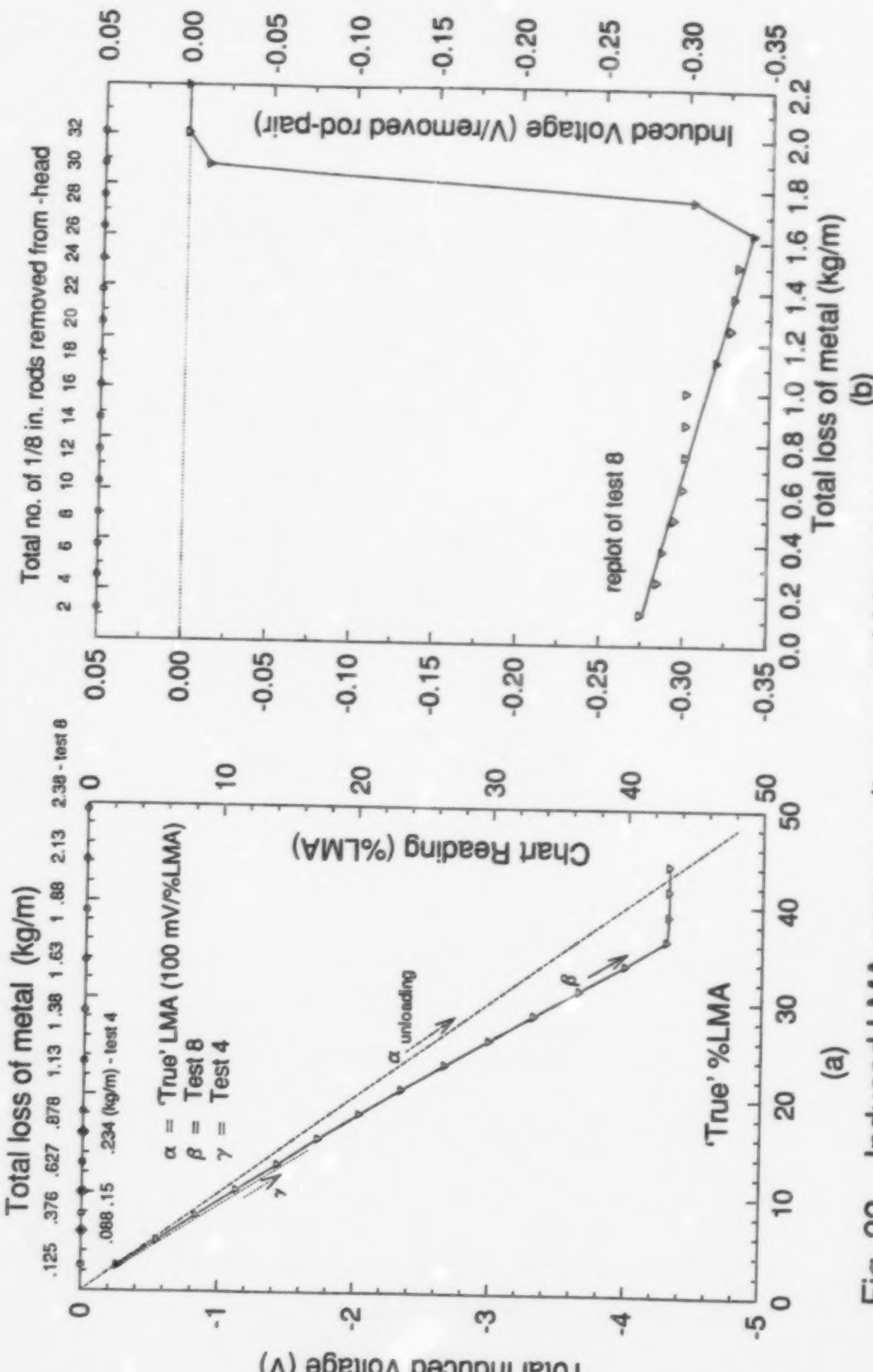


Fig. 22 - Induced LMA-sensor voltage vs %LMA; LMA-250 instrument with tabulated LMA gain of 3.62 (test 4a); 4.32 (test 4b); 1.32 (test 8);

Symmetric, gradual, unloading of 3/32 in. rods from small mock-up (test 4) or of 1/8 in. rods from large mock-up (test 8).

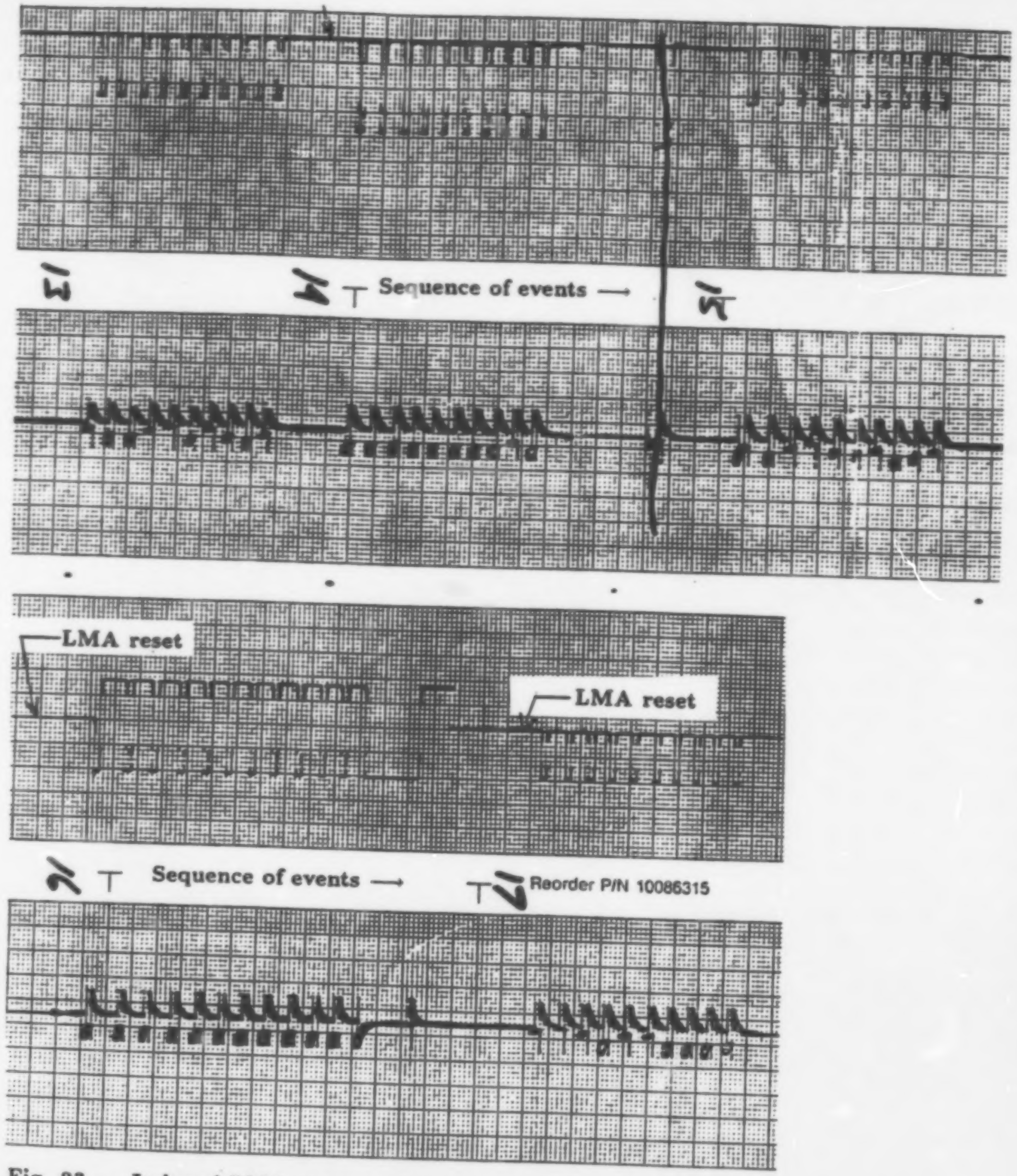


Fig. 23 — Induced LMA sensor voltage vs mass in sensor-head, LMA-250 instrument (test #10a): remove/reinsert (10 - 12 times) rod sizes: (a) $\frac{13}{16}$ in. (step #13); (b) 1.0 in. (steps #14 and #17); (c) $1\frac{5}{64}$ in. (step #15); (d) $1\frac{7}{16}$ in. (step #16); recorder set at 1.0 V/major chart division; LMA Gain Potentiometer dial-setting at 0.5 for steps #15 through 17, otherwise at 1.

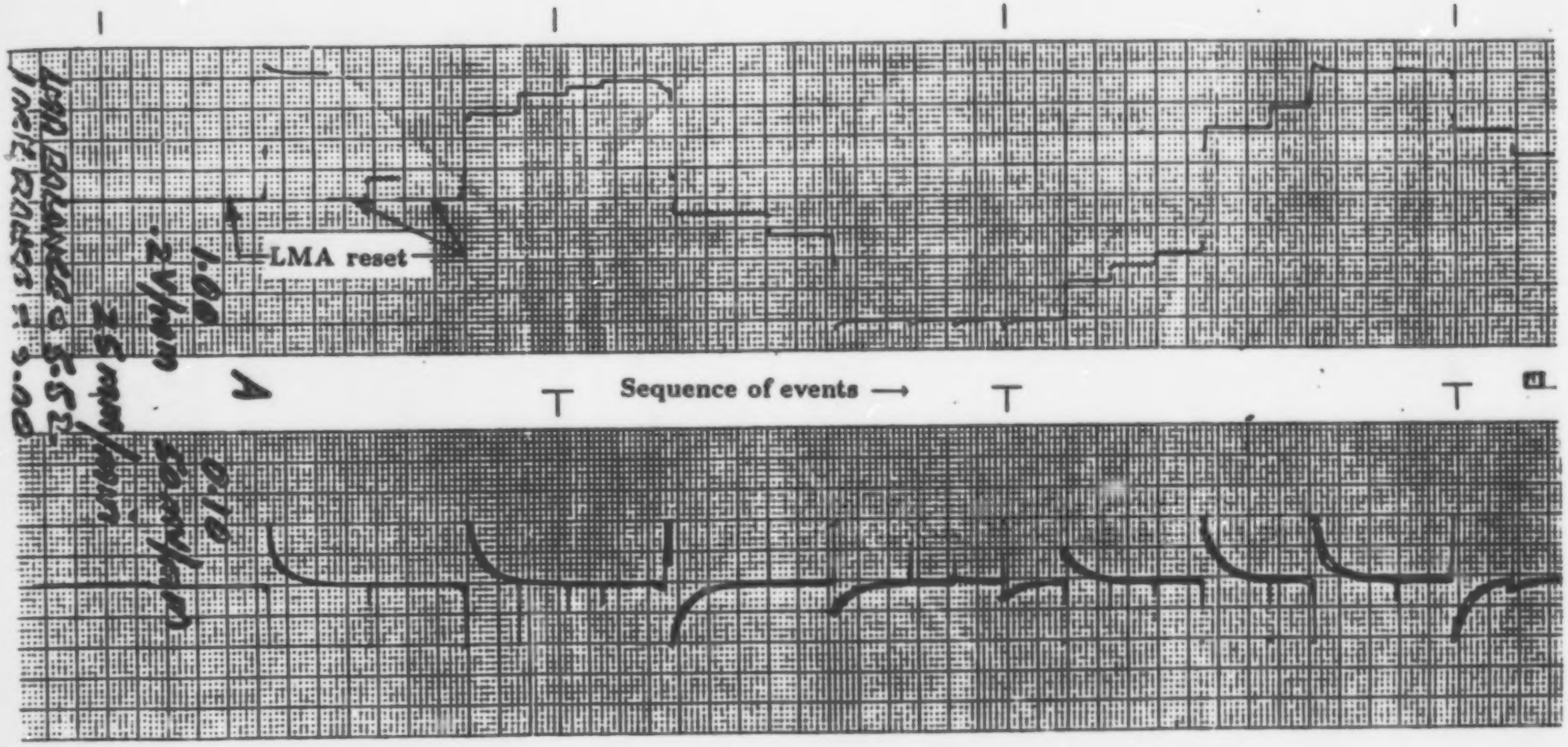


Fig. 24a — Induced cumulative LMA sensor voltage vs mass in sensor-head, LMA-250 instrument (test #9h, run #1): LMA reset; insert $1\frac{7}{16}$ in. rod; LMA reset; insert $\frac{29}{64}$ in. rod; LMA reset; insert $1\frac{5}{64}$ in. + $\frac{37}{64}$ in. + $\frac{23}{64}$ in. + $\frac{21}{64}$ in. rods; remove $1\frac{7}{16}$ in. + $\frac{29}{64}$ in. + $1\frac{5}{64}$ in. + $\frac{21}{64}$ in. + $\frac{23}{64}$ in. + $\frac{37}{64}$ in. rods; reinsert $1\frac{5}{64}$ in. + $\frac{37}{64}$ in. rods; recorder set at 1.0 V/major chart division; LMA Gain Potentiometer dial at arbitrary setting of 1.

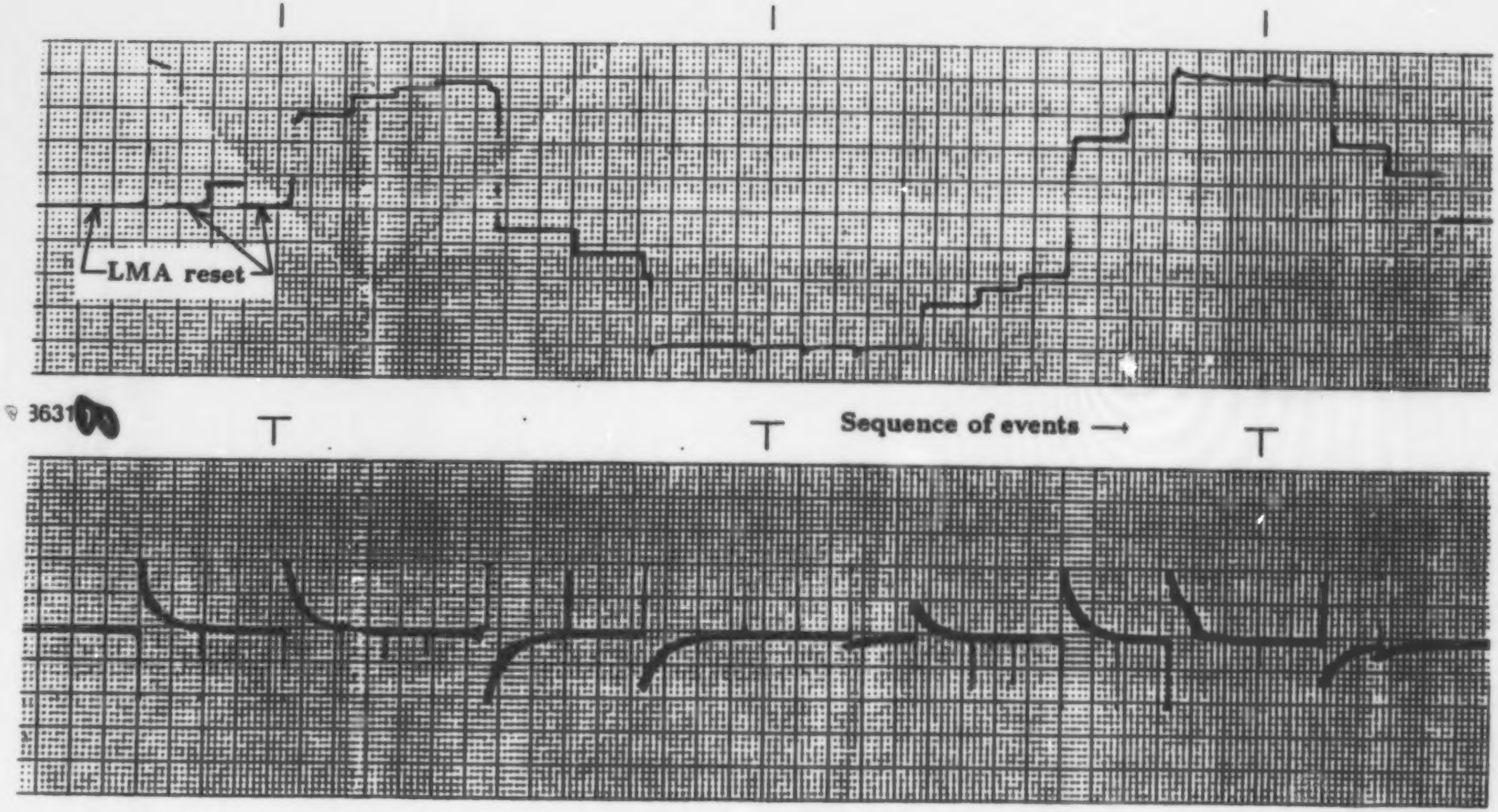


Fig. 24b — Induced cumulative LMA sensor voltage vs mass in sensor-head, LMA-250 instrument (test #9h, run #2): LMA reset; insert $1\frac{7}{16}$ in. rod; LMA reset; insert $\frac{29}{64}$ in. rod; LMA reset; insert $1\frac{5}{64}$ in. + $\frac{37}{64}$ in. + $\frac{23}{64}$ in. + $\frac{21}{64}$ in. rods; remove $1\frac{7}{16}$ in. + $\frac{29}{64}$ in. + $1\frac{5}{64}$ in. + $\frac{21}{64}$ in. + $\frac{23}{64}$ in. + $\frac{37}{64}$ in. rods; reinsert $1\frac{5}{64}$ in. + $\frac{37}{64}$ in. rods; recorder set at 1.0 V/major chart division; LMA Gain Potentiometer dial at arbitrary setting of 1.

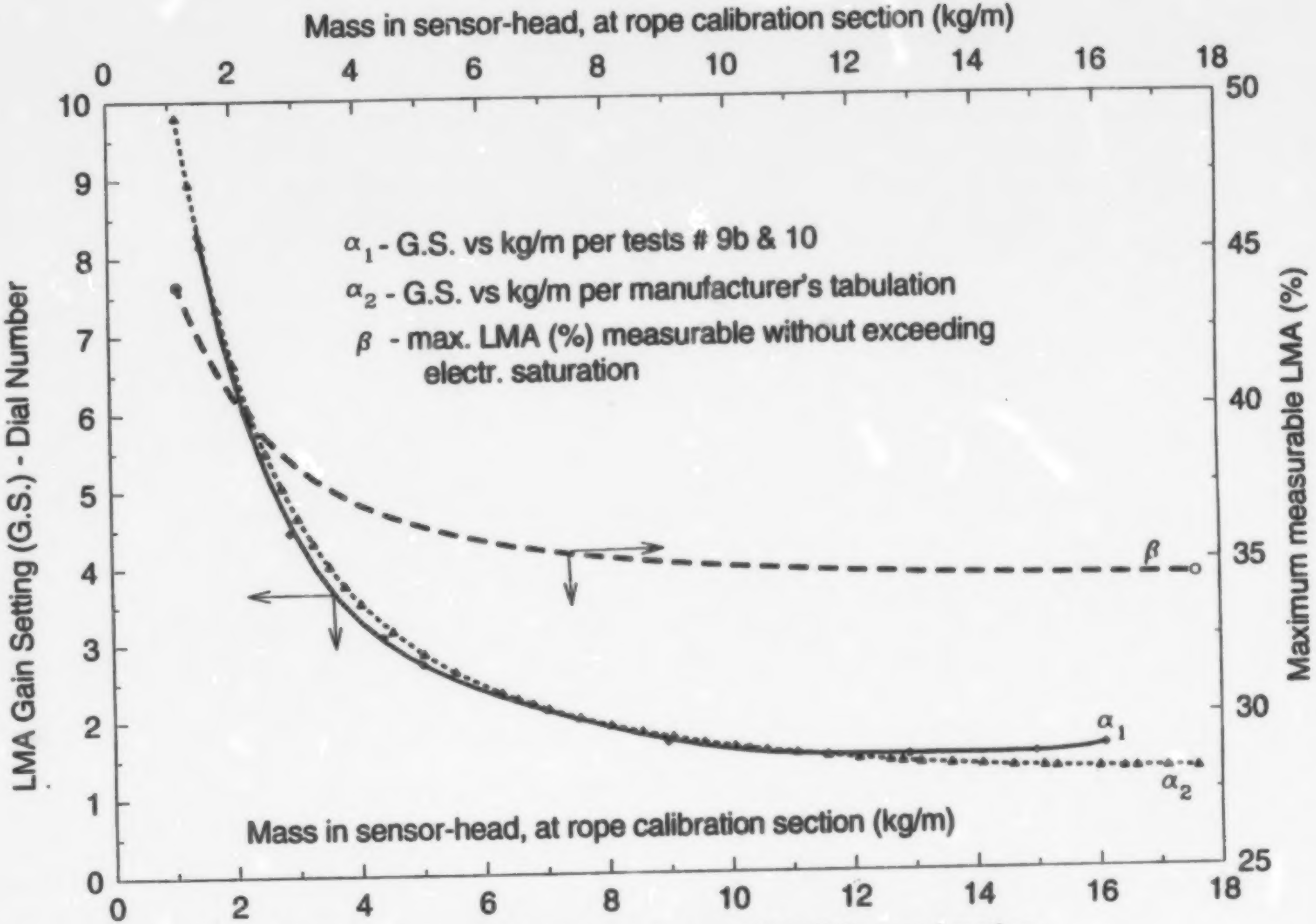


Fig. 25 - LMA-250 instrument: max. LMA (%), as a function of the wire-rope's kg/m at point of calibration, that can be measured without exceeding instrument's electr. saturation level

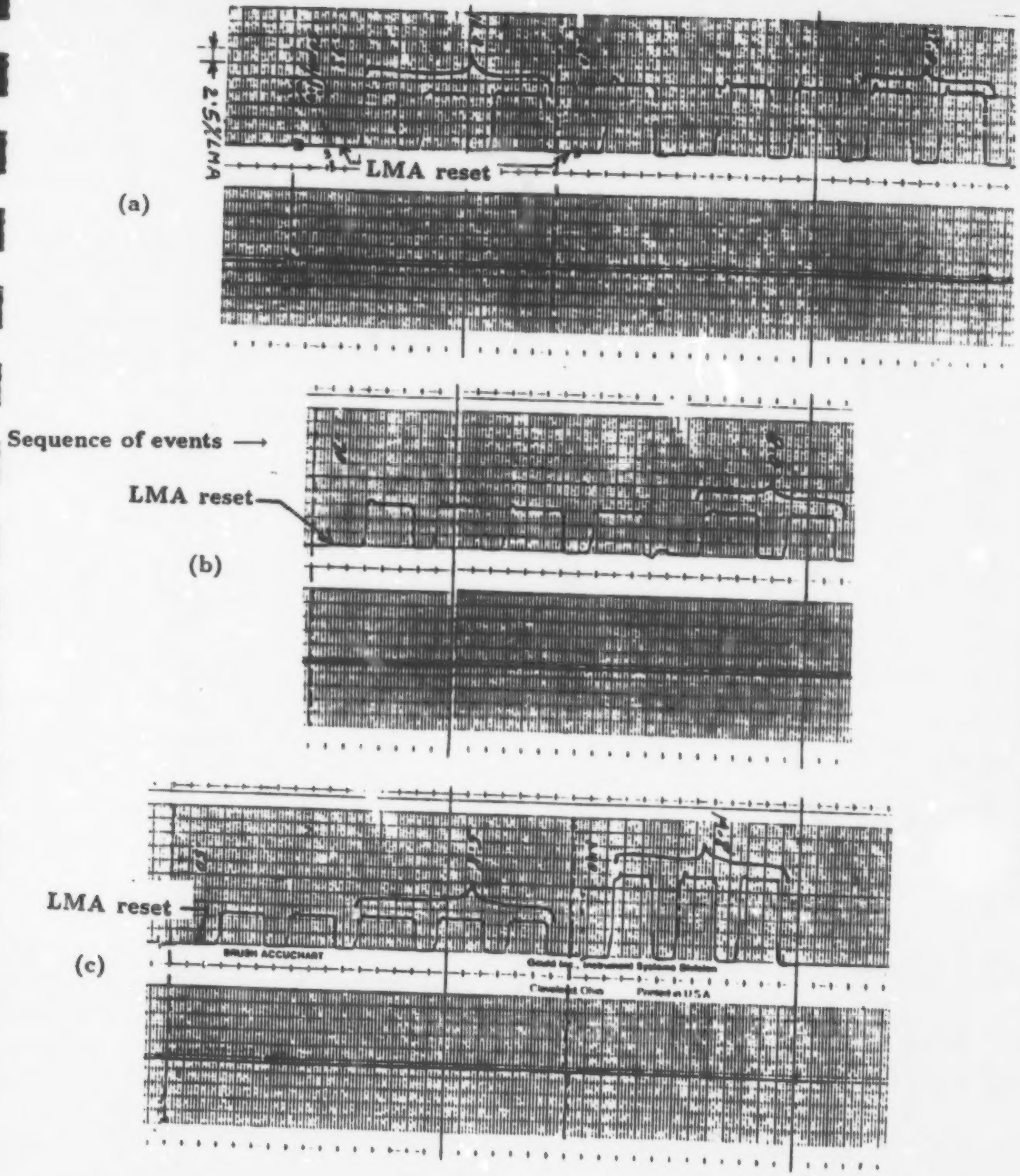
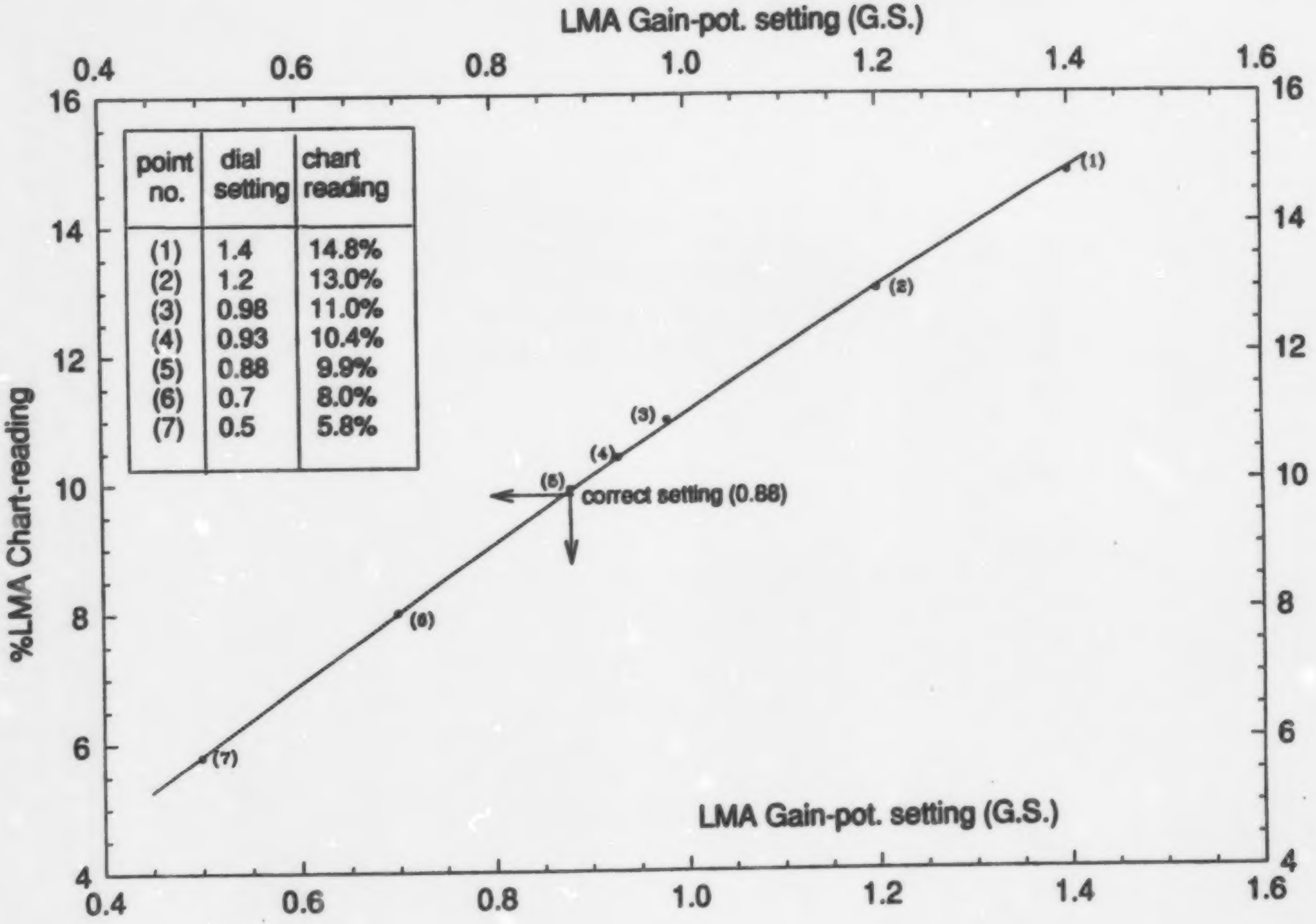


Fig. 26a — Range of chart-readings with LMA-250 instrument (test #11) of a 9.9% 'true' LMA, with gain dial-settings of: (a) 0.93 and 1.20; (b) 0.70; and (c) 0.50 and 1.40, with a recorder setting of 50 mV/chart mm (i.e., with 2.5% LMA /major chart division)



point no.	dial setting	chart reading
(1)	1.4	14.8%
(2)	1.2	13.0%
(3)	0.98	11.0%
(4)	0.93	10.4%
(5)	0.88	9.9%
(6)	0.7	8.0%
(7)	0.5	5.8%

Fig. 26b - Graphical representation of Fig. 26a, i.e., of test 11 results.

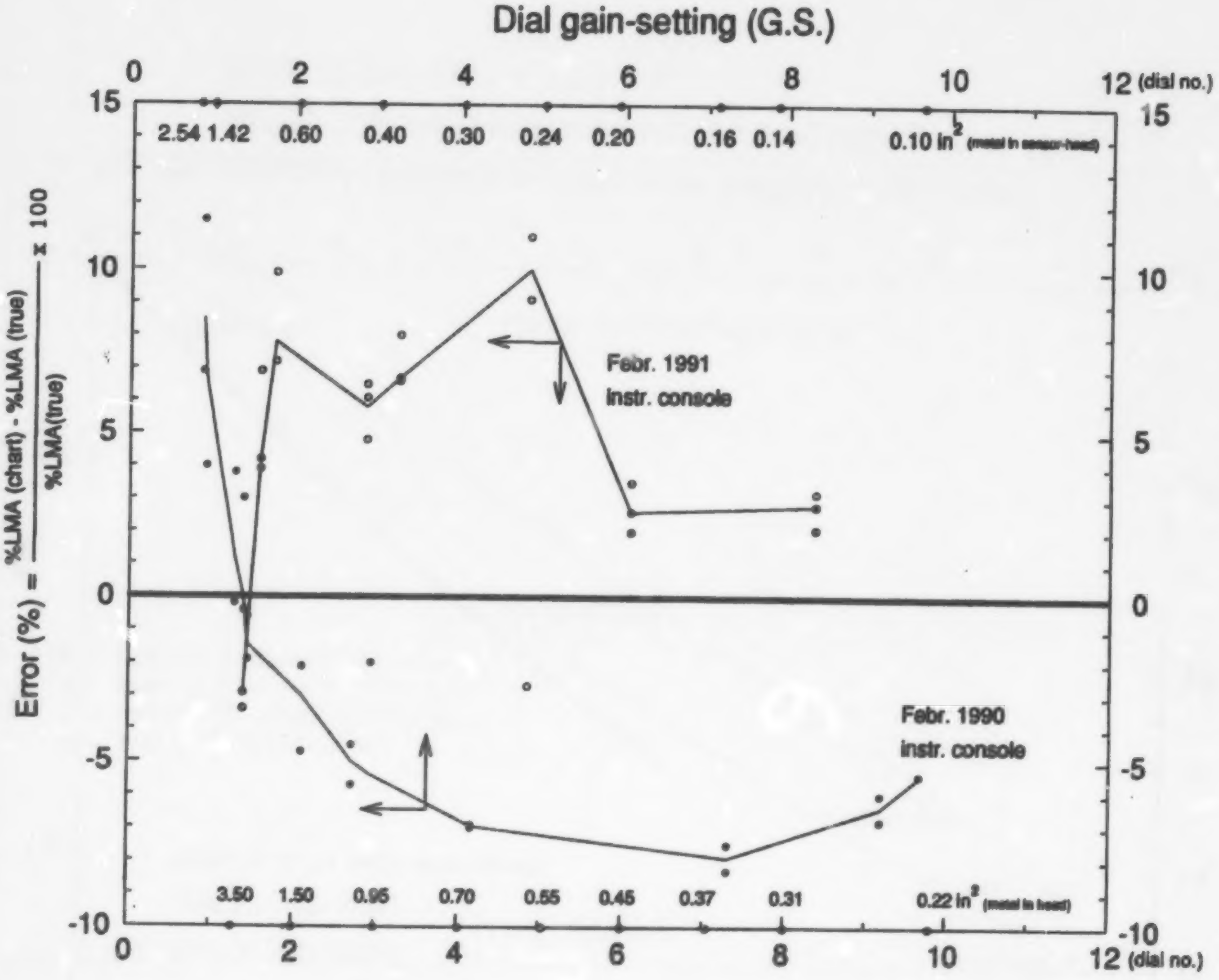


Fig. 27 - Accuracy of %LMA chart-readings (test 10b);
LMA-250 instrument with tabulated LMA gain-settings (G.S.)

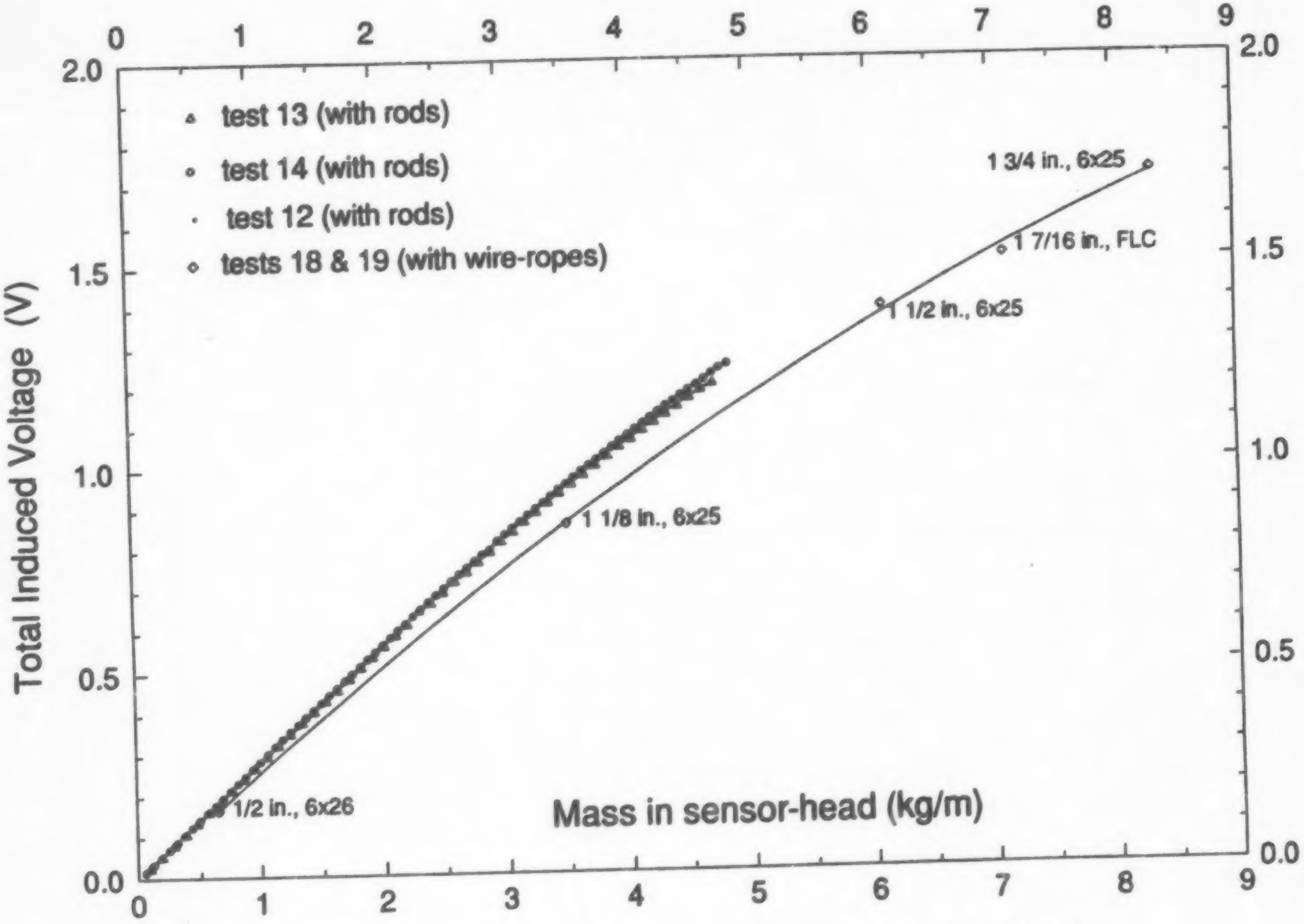


Fig. 28 - Induced LMA-sensor voltage vs mass in sensor-head; MAGNOGRAPH instrument at arbitrary LMA gain of 186; (tests 12 through 14, 18 & 19)

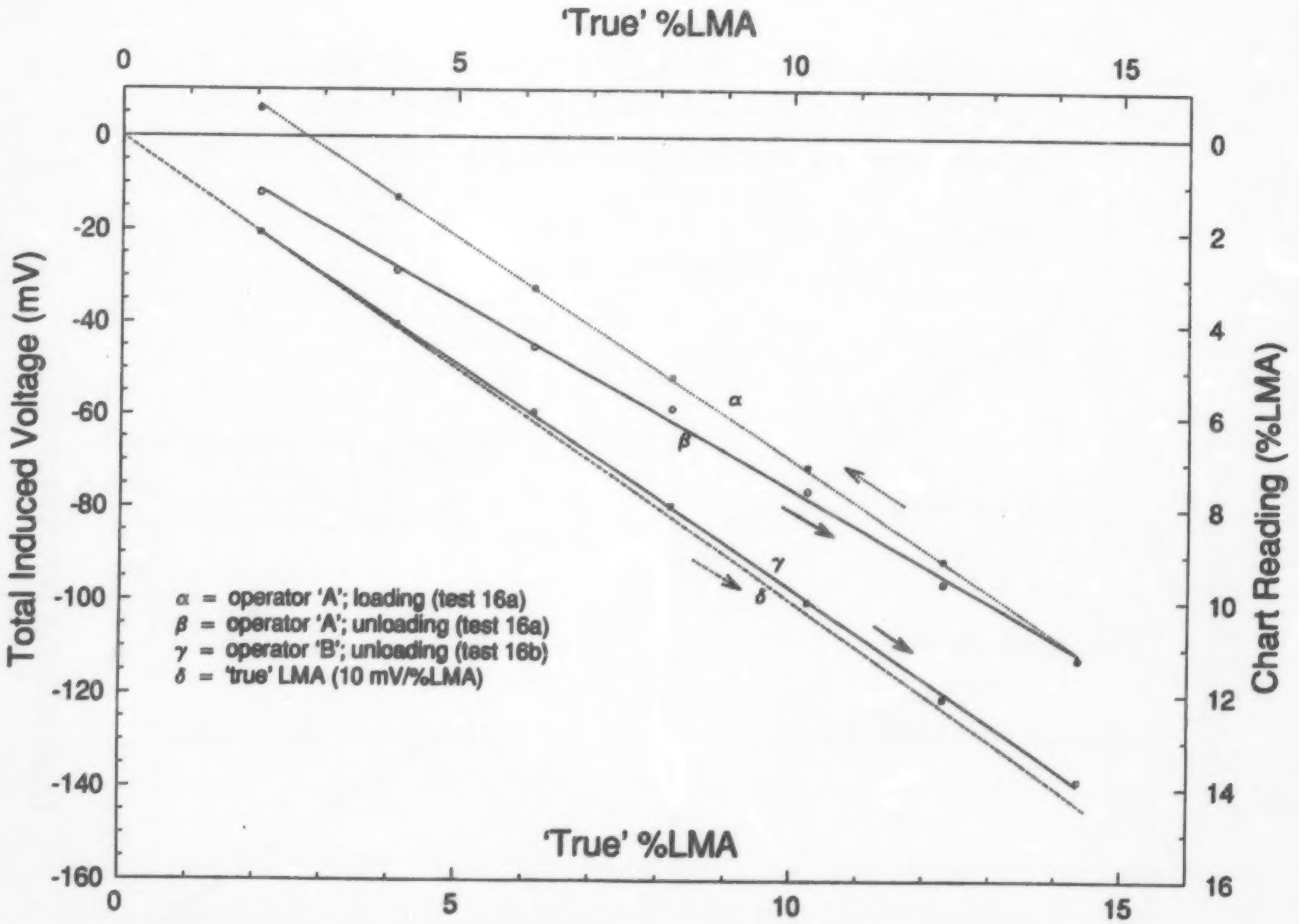


Fig. 29- Induced LMA-sensor voltage vs %LMA (tests 16);
MAGNOGRAPH instrument with calibrated LMA gain setting;
replete large mock-up; symmetric, gradual, unloading of 5/32 in. rods.

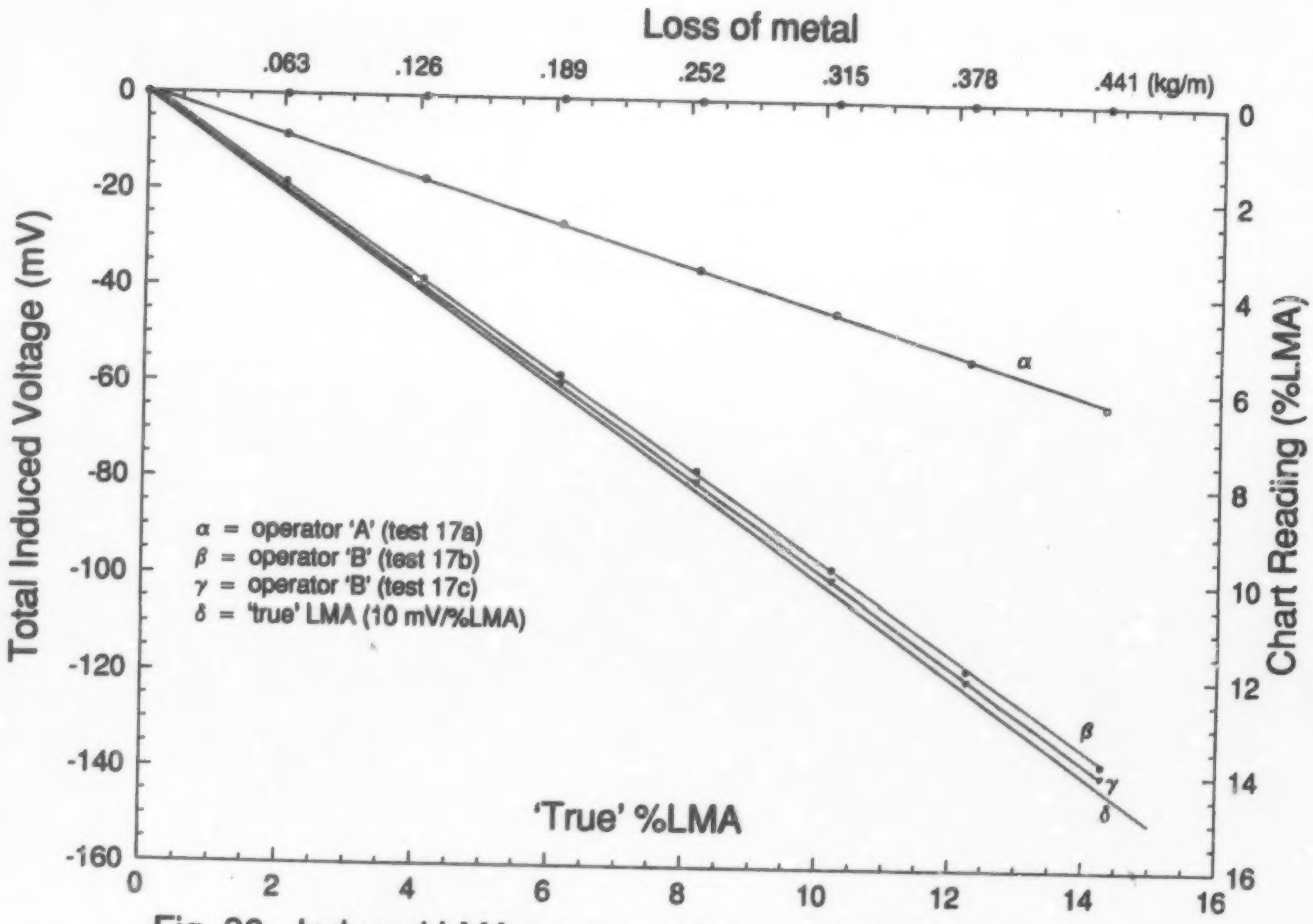


Fig. 30 - Induced LMA-sensor voltage vs %LMA (tests 17); MAGNOGRAPH instrument with calibrated LMA gain setting; replete small mock-up; symmetric, gradual, unloading of 1/8 in. rods.

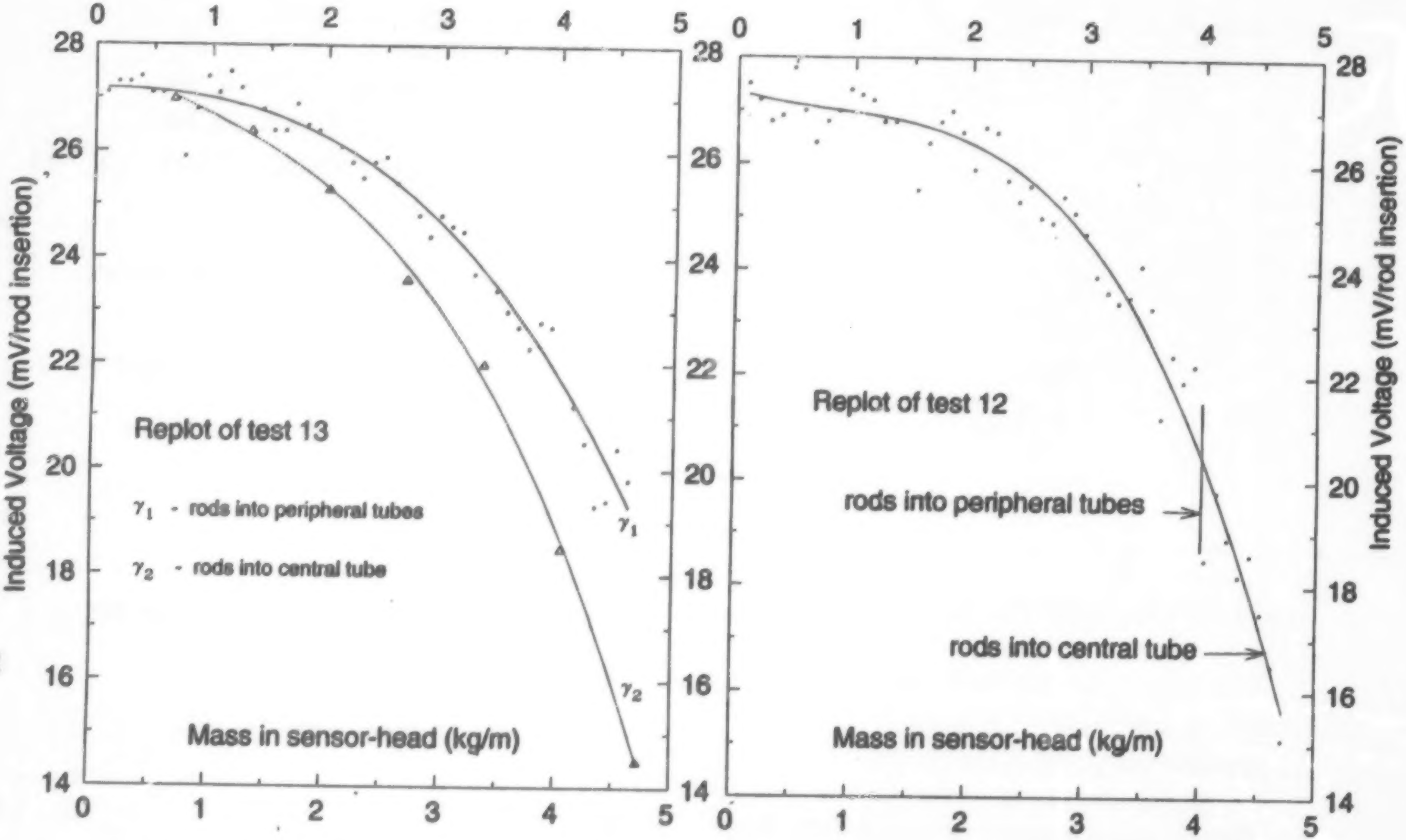


Fig. 31- MAGNOGRAPH instrument; replot of Fig. 28, on a ΔV per rod insertion basis; large mock-up, gradual loading with 5/32 in. rods; arbitrary gain of 186.

Test 13a: all 7 tubes loaded in rotation, concurrently

Test 12: complete loading of 6 peripheral tubes first; finally of central tube

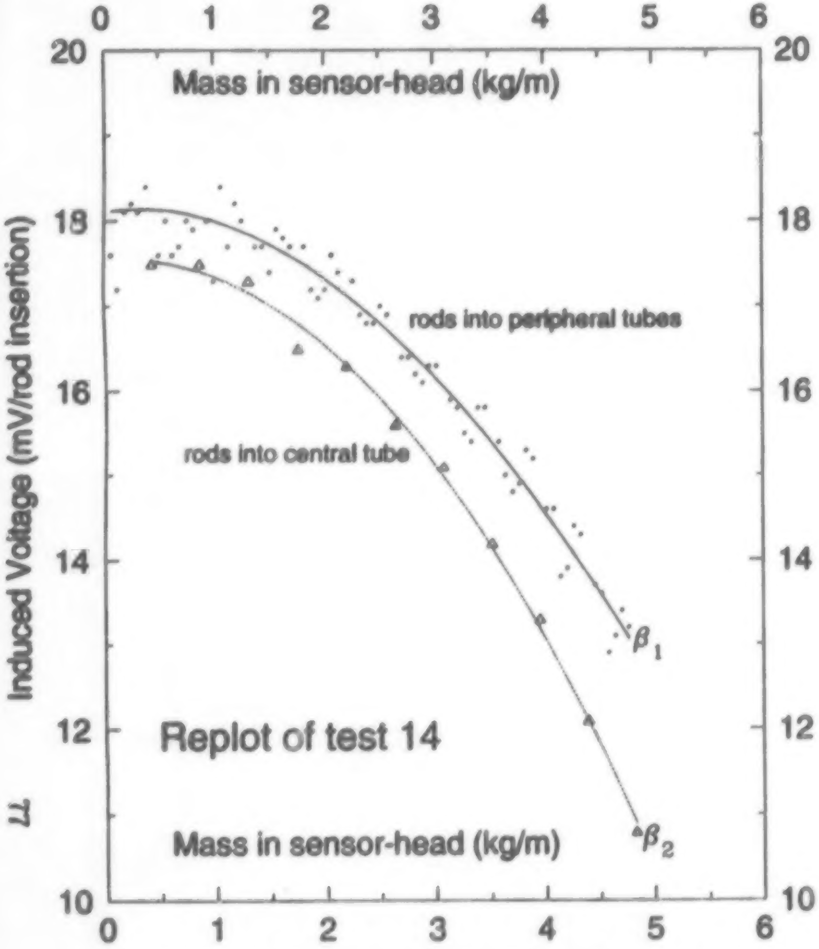


Fig. 32 - MAGNOGRAPH instrument; replot of Fig. 28, on a ΔV per rod insertion basis.

Test 14: as test 13, except for use of 1/8 in. rods (rather than 5/32 in. ones)

Fig. 33 - Induced LMA-sensor voltage vs mass in sensor-head; MAGNOGRAPH instrument at arbitrary LMA gain of 186; (tests 12 through 15)